SOIL TILLAGE, CULTIVATION AND EQUIPMENT SELECTION FOR AGRICULTURAL PRODUCTION ON SMALL AND MEDIUM-SCALE FARMS

Final Draft

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by

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AUTHOR’S NOTE

This document is an extension-oriented manuscript on soil tillage, cultivation and equipment selection for agricultural production on small and medium-scale farms. A systems approach is used and it covers a broad range of soil types and climatic and environmental conditions. This document is intended for use in the training of agricultural extension workers and as a resource manual. It is designed to assist in the analysis of constraints or problems relating to tillage facing farmers, and in selecting and recommending suitable alternative tillage, cultivation and management systems to overcome these constraints.

The Food and Agricultural Organization of the United Nations (FAO), commissioned me to prepare a much shorter version of this document in 1992. However, it was never published and the publishing rights were returned to me. As this document was completed in 1994 much of the information it contains is now necessarily no longer current. In addition, it has never been peer reviewed. It is presented here “as is” and no attempt has been made to update it. I am making it available under a Creative Commons Attribution Non-commercial 4.0 International Licence (see http://creativecommons.org/licenses/by-nc/4.0/), which allows non-commercial use to be made of the work, providing that I am acknowledged as a source in any resulting work.

The current work was greatly influenced by my experiences of working in Zimbabwe from 1982 to 1989, for the latter four years as the Chief Engineer, Head of the Institute of Agricultural Engineering, under the Department of Agricultural, Technical and Extension Services (AGRITEX), in Harare. This information includes the Zimbabwean experience on reduced and zero tillage systems, and of using conservation systems and works to minimise soil erosion. These systems and practices were ahead of most other countries at the time. However, since then there have been significant developments in the field of conservation agriculture, which is the main system now being promoted by FAO and other UN organizations. Some links to these are given below:
http://www.act-africa.org/

As can be seen by going through the list of contents, the information and approaches that were relevant 20 years ago are still largely relevant today with generally only minor modifications required to bring them up to date. A new sub-section on conservation agriculture should ideally be added into Section 3 and the emphasis of the document geared toward conservation agriculture throughout. Of particular importance is the need to emphasise the intercropping of plants with the main crop to achieve the objectives of conservation agriculture. In particular this applies to the use of intercropped plants to act as sources of nutrients to the main crop; to provide resistance to pests, diseases and weeds; to promote soil conservation; to act as fodder crops; or sources of additional income to the farming household. Several examples of these are given in the document but greater emphasis needs to be placed on them. Numerous examples are given in the links above and one particular system in the following link:
http://www.peopleandtheplanet.com/index.html@lid=27731&section=34&topic=27.html

I have not included any diagrams and illustrations as the majority are subject to copyright. They are, however, clearly referenced and should anyone select all or part of this document to use they could easily find them. Also anyone knowledgeable in this field and with access to the Internet could readily find alternative illustrations or diagrams.

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PREFACE

Soil tillage forms the basis of crop production systems and is a major factor in determining their success or failure. The selection of inappropriate tillage practices has a major adverse impact on sustainable crop production and on soil erosion on arable lands. With the increasing world population, and the resultant increase in pressure on the limited arable land available, it is vitally important that tillage practices are used which result in sustainable and productive farming.

This document deals with tillage in crop production systems with an emphasis on small and medium-scale farms. Those aspects of cultivation and management systems that interrelate with soil tillage are also covered. Emphasis is placed on tillage in the arid and semi-arid climatic regions, but the temperate and humid tropical regions are also covered.

This document is intended for use in the training of agricultural extension workers and as a resource manual. It is designed to assist in the analysis of constraints or problems relating to tillage facing farmers, and in selecting and recommending suitable alternative tillage, cultivation and management systems to overcome these constraints. The physical and organic properties of soils and the basics of soil tillage are covered in detail. Tillage systems and the means of implementing the tillage operations are described in detail, together with the equipment used, its general cost and its maintenance requirements. Manual, animal and motorised power sources are covered. The close way in which soil tillage interrelates with the farmer's resource base and other farm management concerns in crop production is emphasised throughout.

This document has been designed for use both by extension staff who are specialising in the fields of soil tillage and mechanisation, as well by general extension workers who do not require this depth of information. Furthermore, it is designed for use both by senior and junior extension workers. To cater for those groups requiring an in-depth coverage, the subject has been covered comprehensively, including the theoretical basis of tillage, and the economic, management and strategy aspects have been emphasised throughout and the implementation of the various tillage operations is given in detail. Research evidence to support the conclusions has also been presented and sufficient details of tillage operations and relevant crop characteristics, etc., have been included for this publication to be used as a resource book. To cater for those requiring a less in-depth coverage, the layout has been designed so that it is highly compartmentalised, so that it is easy to skip components which may be too detailed, or which are covered adequately in other training courses. Furthermore, the first few paragraphs of each section give an overview of the section and point out the relevance of the section to tillage and crop production in general, so that readers can appreciate the relative importance of the subject under discussion to their requirements and can decide whether they wish to complete the section. For some readers it may be possible to skip the whole of Section 2 as some of the main points covered there are summarised in relation to several basic types of tillage systems described in Section 3. When complex interactions are described these have been laid out in point form before being described in detail. The main points from graphs and tables have also been highlighted to assist junior staff in their interpretation. As junior extension workers are generally taught by senior extension workers it is hoped that the above will facilitate the use of this publication as an effective resource book for their training and the extraction of classroom training material.

As much relevant research work is ongoing in the field of soil tillage and soil and water conservation, it is important that senior extension workers keep up to date on the latest findings through the latest research publications. Most research papers in the tillage field assume an in-depth knowledge of the subject by their readers and so an attempt has been made to include in this publication the essential background information required. The SI units of measurement are used in this publication and the common units and magnitudes of the various parameters discussed are given to enable readers to develop a feel for the range that can be expected.
For those readers who intend to study this whole document in detail the following initial procedure is recommended:

. Firstly, read the introduction and then skim through the introductory paragraphs of the major sections.
. Secondly, skim through Section 9 and especially Section 9.2, which is in effect a very brief summary of the major subjects covered in this publication.
ACKNOWLEDGEMENTS

The preparation of this publication has been based to a large extent on the previous publications in this field by FAO. In particular, in the sections on the physical and organic properties of soils, very extensive use has been made of the FAO publication, "Agricultural engineering in development: tillage for crop production in areas of low rainfall", by R. J. Godwin. In this area of soil science extensive use was also made of the book by N. C. Brady, "The Nature and Properties of Soils".

In the sections on cultivation and management systems extensive use has been made of the FAO publication, "Tillage systems for soil and water conservation", by P. W. Unger. Some of the key references given in this last publication have also been listed here. The GTZ publication "Soil Tillage in the Tropics and Subtropics", by R. Krause, F. Lorenz and W. B. Hoogmoed, has also been used extensively, particularly in the section on tillage implements. The detailed methodologies for the implementation of the various tillage operations are based primarily on the extension material published by The Department of Agricultural and Extension Services (AGRITEX) in Zimbabwe. This material was originally developed under a joint project between AGRITEX and GTZ at the Agricultural Engineering Training Centre of the Institute of Agricultural Engineering in Zimbabwe.

Most of the illustrations and tables referred to have been derived from the publications listed above. The original sources of all illustrations and tables used are listed but not included in this draft.
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1. **INTRODUCTION**

For successful and sustainable crop production it is very important that all the components of the crop production system are viewed as parts of a coherent system. These components, including the tillage, cultivation and management systems, must be complementary to each other and appropriate to the region, the farm and the farmer. This publication deals primarily with soil tillage, but also with those aspects of crop cultivation and management systems that are directly interrelated with soil tillage.

While it is important to analyse and plan tillage operations and systems as part of the whole crop production system, this can only be done if all the individual factors affected by tillage, and which determine the choice of tillage operations and systems, are understood. The first part of this publication therefore looks at these factors in detail. Because a large number of these factors are involved, and because they vary substantially from region to region and farm to farm, it is not possible to come up with a particular tillage package that would be generally suitable for a specific region. This is particularly true of a publication like this one, which is designed for use within regions having a wide range of climatic characteristics, soil types, general infrastructure, etc. For this reason it is considered very important that extension workers understand the way in which each of the factors involved affect the choices to be made, as well as the likely problems which will be incurred by the inevitable compromises which have to be made.

The main factors involved in the choice of tillage system, and the ones involved in the analyses of problems relating to tillage systems, are discussed individually and in detail in Section 2. This is the largest section within this publication. These factors are then drawn together in Section 3 when whole tillage systems are discussed, and the advantages and disadvantages of the basic types of tillage systems are described. This section continues with a discussion of cultivation and management systems and how these interact with tillage systems, and can be used to complement them. Most of the remaining sections cover the detailed implementation of tillage operations, and aspects associated with the cost and maintenance of tillage implements and power sources. Section 8 summarises the main aspects covered in the preceding sections, in the form of laying out a methodology for the analysis of problems in tillage and for the selection of appropriate tillage systems.

The sustainability of the crop production systems, in terms of minimising soil and nutrient loss through erosion and minimising the loss of soil organic matter and soil water through excessive tillage, and in controlling weed, pest and disease levels is emphasised throughout. The different economic frameworks within which the farmers operate, and how these determine their objectives and limit the range of options open to them, both with regard to the choice of tillage systems and how to implement them, are also emphasised.

1.1. **DEFINITION AND OBJECTIVES OF SOIL TILLAGE**

Soil tillage is the mechanical manipulation of the soil within a crop production system. The overall objective of tillage is the modification of the physical, chemical and biological characteristics of the soil, so as to provide the optimum environment for the germination and development of the plants, and so enhance growth and yield.

The specific objectives of tillage include; the maintenance or improvement of soil structure and its infiltration, storage and drainage characteristics; the limiting of soil and nutrient loss through soil erosion; the mixing or incorporation of crop residues, manures, etc.; the enhancement of the accessibility of plant nutrients; the provision of a suitable seedbed and rooting environment; and the control of weeds and pests. These objectives are given in more detail in Section 5.3.
Soil tillage is an intrinsic component of crop production and hence its objectives are also largely determined by the objectives of crop production. These objectives will vary from farmer to farmer, with the commercial and subsistence farmer being at either extreme. The crop production objectives of the commercial farmer may be maximum yield, or maximum return on capital and running expenses, including the cost of implementing tillage systems, or highest quality of product, etc. The crop production objectives of the subsistence farmer may be limited to the production of sufficient food for the household for one year with the minimum expenditure of cash and labour, and also importantly, with the minimum exposure to risk. However all farmers still desire to maximise returns over inputs, even though the inputs and desired returns may vary substantially from farmer to farmer.

1.2. THE IMPORTANCE OF SOIL TILLAGE IN CROP PRODUCTION

Soil tillage forms the basis of crop production systems, as the tillage system chosen not only determines the initial land preparation required before planting but also substantially affects all the field operations that follow. The tillage system used will directly affect a large number of factors, including: soil structure and organic matter content; plant available moisture; susceptibility to soil and nutrient loss through erosion; seedling germination; level of weed and pest problems; the type of equipment, power sources and labour required for tillage and the control of weeds and pests; the timeliness of operations; the harvesting method and implements to be used; the cost of production; and the yield of the crop.

The selection of tillage systems suitable for sustainable crop production, that also maximise the returns over inputs to the farmer, requires a detailed knowledge of the various factors involved and an ability to select the most appropriate compromises. This is not an easy task as almost every tillage operation has both beneficial and adverse effects on different soil parameters as well as implications for all subsequent field operations. For example, frequent tillage operations to control weeds to reduce competition with the crop for water, or to loosen the soil to promote water infiltration, may also increase the loss of organic matter in the soil and thus reduce the water holding capacity of the soil and also reduce its nutritional status. Furthermore frequent tillage operations are likely to reduce the degree of soil aggregation and lead to an increased risk of erosion. Another example would be the use of zero tillage systems in order to reduce the draught power input requirement. These systems are usually only sustainable if crop residues are left as a surface mulch to reduce soil and water loss. However crop residues severely restrict the range of weeding implements that can be used and also frequently lead to increased pest levels in the growing crop. Furthermore crop residues are frequently not available as a surface mulch as they often form an important food source for cattle during the dry season.

There are many contradictory demands in agricultural production and successful farming is largely dependent on good management by the farmer. This is particularly true of the timeliness of operations in the arid and semi-arid areas, and the tillage system selected for crop production significantly determines the possibility of timely operations, given the usually poor resource base available to small and medium-scale farmers in these areas.

1.3. SOME INITIAL ECONOMIC ASPECTS CONCERNING TILLAGE

Although soil tillage is a very important component within crop production its contribution to the total cost of production may be fairly low. For example, if the cost of tillage within a crop production system is 10% of the total cost, then a reduction of 20 % in tillage costs would only relate to a 2 % reduction in overall crop production costs, all other factors remaining equal. In this case small or medium-scale farmers would be unlikely to change the tillage system they use solely to reduce costs and would probably prefer to remain with the systems that they are used to managing.
Farmers will also rarely change their usual tillage system to reduce soil erosion, as the effects of soil erosion on yield are usually not apparent in the short term. If extension workers are to be successful in promoting improved tillage systems they will therefore generally have to do this on the basis of criteria, which are of immediate importance to the farmer, such as, reduced labour requirements or substantially increased yields due to reduced water runoff.

It is very important that extension advice is specifically geared towards the particular resource base and requirements of the farmers being advised. If this is not done totally inappropriate advice may be given. This aspect should be borne in mind not only when selecting tillage operations and systems, but also when considering the implications of these choices for the rest of the crop management system.

One particular point that must be emphasised early in this publication is that many small and medium-scale farmers intuitively manage their farms on a low risk strategy as opposed to a strategy of maximising crop production. This is particularly true of resource poor farmers in the arid and semi-arid areas. Failure to appreciate this has often led extension workers to wrongly categorise some farmers as stubbornly conservative for not adopting the recommended extension packages. For example many farmers in arid areas do not follow the standard recommendations of applying fertilizer with their seed during dry planting and will wait for the onset of reliable rains before applying it. In areas where there is a likelihood of total crop failure two years out of five this strategy of conserving expensive fertilizer may make good financial sense for a resource poor farmer, even though it leads to reduced yields in those years when rains are adequate and crops are harvested.

1.4. TILLAGE OPERATIONS AND SYSTEMS

Tillage systems are defined on the basis of the type and intensity of the various tillage operations that are involved in making up the system. These are briefly defined below and will be discussed further in later sections.

1.4.1. Tillage Operations

Tillage operations are usually divided into primary and secondary tillage operations. Primary tillage refers to the main, and usually deep, tillage operations undertaken between two crops to loosen the soil down to rooting depth and to prepare the land for further operations. Secondary tillage refers to those shallower operations undertaken after primary tillage to prepare the seedbed and to manage the crop. A more complete grouping of tillage operations is given below in the sequence in which they are generally performed for a new crop under a conventional tillage system:

a. Stubble or post-harvest tillage:
   Shallow tillage carried out shortly after harvest to remove weeds, and possibly cover crop residues, and to modify soil structure. This includes tillage during fallow periods for water conservation, weed control and improvement of the soil structure and fertility.

b. Primary tillage:
   Deep tillage undertaken between two crops to modify the soil structure in the main rooting area of the next crop, primarily soil loosening, to mix or incorporate crop residues, animal manures, etc., to control weeds and to prepare the land for seedbed preparation.

c. Seedbed preparation:
   Shallow tillage to prepare seedbed or to prepare for transplanting. Includes weed control and the preparation of a fairly finely granulated soil structure, to promote good seed/soil contact so as to facilitate germination and early growth. Also sometimes includes the formation of beds and ridges to facilitate harvesting of root crops or to
improve soil and water conservation.

d. Crop management tillage operations:
   Shallow operations to control weeds, break up surface crusts to aid crop emergence
   and improve water infiltration.

Groups a, c and d above are classified as secondary tillage in the primary/secondary
tillage classification system, and this system is used below for ease of description. However,
this two-part classification system does suggest that tillage for a new crop starts with primary
tillage, e.g. ploughing, immediately before planting. Whereas the a. to d. grouping above
emphasises the importance of starting tillage preparations for the new crop at as early a stage
as possible. In terms of tillage this can be done immediately after harvest through weed
control, to reduce water loss through evapotranspiration or subsequent weed infestation, or the
loosening of the surface soil structure to improve water infiltration, or the creation of a soil
mulch to reduce evaporation, etc. In terms of crop production as a whole it needs to be
emphasised that most preceding operations on a field will affect future crop production,
especially in terms of nutrient levels and weed and pest infestation problems. The
implementation of the complete sequence of tillage operations listed above may not be
necessary or desirable. This will depend on the time available for the tillage operations and on
other aspects of the whole crop production system.

The main primary tillage operations include: sub-soiling and ploughing using
mouldboard, disc or chisel ploughs. The main secondary tillage operations include: harrowing
and cultivating, using harrows and cultivators with rigid and sprung tines, discs and various
rotary soil engaging attachments. The construction of ridges and furrows or beds for planting
using ridger bodies or lister ploughs is another important secondary tillage operation. In-field
soil moving operations which are not classified as tillage operations, but affect the
effectiveness of tillage operations, include land smoothing and levelling, the construction of
mechanical conservation works, terracing, etc.. Details of these operations and the machinery
required to implement them are given in Section 4.

1.4.2. Tillage Systems

Tillage systems are usually categorised according to the level of intensity of tillage
operations used to make up the system and whether or not they are geared towards the
conservation of soil, water and energy. There is little standardisation in the names used but the
most commonly used are defined below:
   a. Conventional Tillage:
      Conventional tillage systems involve intensive tillage operations with any remaining
crop residues fully incorporated into the soil. This involves full depth ploughing with
complete inversion of the soil, one or more cultivation operations prior to planting, and
cultivation and/or herbicide weed control. Planting may be on the flat, on beds or on
ridges. Conventional tillage may also be required in a field prior to moving onto reduced
or conservation tillage systems to overcome specific problems.

b. Reduced Tillage:
   Reduced tillage systems use fewer tillage operations than conventional tillage in order
to reduce the energy input required for tillage, and sometimes to reduce soil
disturbance. Primary tillage operations do not usually include the use of mouldboard or
disc ploughs, or at least not every cropping season. Crop residues may be removed or
partially incorporated. Any crop residues left on the surface will cover less than 30% of
the surface area, otherwise the system is classified as a conservation tillage system.

c. Conservation Tillage:
   Alternative names used are minimum tillage, trash farming, crop residue farming, crop
mulch farming. These are tillage systems where the number of tillage operations are
minimised to reduce energy requirements, and to reduce soil disturbance and where
the crop residues are left on the surface to aid soil and water conservation. At least
30% of the soil surface should be covered with crop residues at the start of the season to classify as a conservation tillage system. Primary tillage operations are excluded. The most extreme form of this system is no-till or zero-till, in which no tillage is undertaken and the only soil disturbance is during the placement of seeds and fertilizers, with herbicides being used for weed control.

Several authorities only differentiate between conventional and reduced tillage systems with conservation tillage systems being one of the reduced tillage systems.

Recent trends in tillage have been to reduce the level of tillage intensity and to move towards conservation tillage systems. This has been done primarily to promote the conservation of soil and water resources in arid and semi-arid regions, and to establish more productive, stable and sustainable systems of farming, as well as to reduce the energy input required and improve farming efficiency. From the perspective of the small and medium-sized farmer these attributes of conservation tillage systems are highly desirable. However, a much higher level of management is required, due primarily to increased weed and pest problems, and herbicides are often also required. Both of these factors have severely limited the adoption of conservation tillage systems among resource-poor farmers.
2. MAIN FACTORS TO BE CONSIDERED WHEN SELECTING TILLAGE OPERATIONS AND SYSTEMS

As stated in the last section the overall objective of tillage is the modification of the physical, chemical and biological characteristics of the soil, so as to provide the optimum environment for the germination and development of the plants on a sustainable basis. When selecting which soil properties to modify and how to modify them, a large number of factors need to be taken into consideration and this must also be done within the context of the whole crop production system. This procedure is further complicated because many of these factors interact with each other.

In this section the main factors to be considered when selecting tillage operations and tillage systems, and when analysing problems relating to tillage, will be discussed. The main factors discussed are the properties of soils; soil erosion; climate; agronomic factors; economic and resource factors; and farmers' preferences, social influences and government policies. How the combination of these various factors lead to different choices of tillage, cultivation and management systems will then be discussed in the Section 3. A basic guidance methodology for on-farm problem identification and the selection of appropriate tillage operations and systems is given in Section 8. Details of the objectives and methods of implementing the main tillage operations, the equipment required and the financial and maintenance considerations are given in Sections 5, 6 and 7.

2.1. SOILS

In this section soils and their basic properties will be discussed together with how tillage operations are used to alter key soil properties in order to enhance profitable and sustainable crop production. Following a brief overview of soils the discussion will concentrate on their properties, how these can be altered, and the ways in which these affect plant growth.

Most of this section is based very closely on the information presented by FAO (1990) and this source can be referred to for a more detailed description of soil properties. A detailed and excellent study of soils is given by Brady (1990), and this source is also used extensively in the following sections.

2.1.1. A Brief Overview of Soils

This overview of soils will briefly cover the constituents of soils, their formation and classification. In effect this sequence will first of all view the soil from the microscopic perspective and then lead on to a view of soils in the field as large dynamic systems, which can be classified into different groups having individual characteristics.

2.1.1.1. The Constituents of Soils

Soil is composed of individual mineral and organic matter particles, together with aggregates of these particles bonded to each other, with spaces called pores between these solid particles containing air and water. Two basic groupings of soils are defined below:

Organic Soils: Those containing more than 50% organic matter by volume (at least 20% by weight), e.g. those soils found in wetland areas, such as marches.

Mineral Soils: These generally contain from 1 to 6% organic matter and are the most common soils. The top layers of a mineral soil in good condition consist of roughly 50% soil solids and 50% pore space by volume. At optimum conditions for plant
growth roughly half the pore space is filled with water and the rest with air. These constituents are not uniformly distributed through the soil.

The vast majority of land that is cultivated is composed of mineral soils and this publication will deal only with these soils. The mineral constituents of soils are derived from rocks and the organic matter is derived from plant and animal residues.

A. Soil Mineral Constituents.

The characteristics of the mineral constituents of soils are largely determined by the rocks from which they are derived and the extent to which weathering has occurred.

The rocks are commonly classified as igneous, sedimentary, or metamorphic, based on their origin. Igneous rocks are those formed from molten magma, including such common rocks as granite and diorite. They are composed of primary minerals such as quartz and the feldspars. Sedimentary rocks have resulted from the deposition and recementation of weathering products of other rocks over a very long time. For example, sandstone is the result of quartz sand being weathered from a granite, then deposited and then through geological changes cemented into a solid mass. Similarly, shale is formed from recemented clays. Metamorphic rocks have formed by the metamorphism, or change in form, of the other two classes of rocks, when subjected to tremendous pressures and high temperatures. Igneous rocks are commonly modified to form gneisses or schists. Those of sedimentary origin, such as sandstone and shale, may be changed to quartzite and slate, respectively.

The process of weathering is a combination of physical disintegration and chemical breakdown and synthesis. Weathering starts with rocks being broken down physically into smaller rocks and eventually into the individual minerals of which they are composed. Sand particles are commonly made up of individual minerals. Simultaneously, rock fragments and the minerals therein are broken down chemically and changed to new minerals. Chemical changes are accompanied by a continued decrease in particle size and by the release of soluble constituents. Some of these soluble constituents are lost in drainage water and some are recombined into new minerals, including the clays.

Climatic conditions are the main factors that control the rate and nature of weathering. Under arid conditions where physical forces dominate, the size of particles is decreased with relatively little change in composition. The original primary minerals, such as quartz, are more prominent, whereas minerals that require water for their synthesis are less so. Consequently, the soils of arid regions are remarkably like the parent materials from which they were formed. In humid regions, however, the physical disintegration of particles is accompanied by vigorous chemical changes. New minerals such as silicate clays and oxides of iron and aluminium are more evident. This process is intensified by the decay of large quantities of organic matter coming from the abundant plant growth.

The mineral particles present in soils vary greatly in size, and these have been generally divided into the following ranges; cobbles (>50mm); gravel (50 to 2 mm); sands (2 to 0.05 mm); silts (0.05 to 0.002 mm); and clays (<0.002 mm). The smallest clay particles have a very large surface area per unit of mass and have colloidal properties. Colloids are defined as very small particles dispersed through a second medium. Clay and organic matter particles smaller than about 1 micrometre in diameter are generally considered to be colloidal in size.

The typical properties of these different size categories of mineral particles are shown in Table ____ (@ Brady 1990, p 12, Table 1.1). From the table it can be seen that both physical properties and the ability of a given soil to supply chemical nutrients to plants are determined to a considerable extent by the proportions of different sized particles which make up that soil. Because of the importance of this, soils are classified into various textural classes based on the proportions of different sized particles that make up the soil, and these classes will be
Minerals that have persisted with little change in composition since they were extruded in molten lava (e.g., quartz, micas, and feldspars) are known as primary minerals. They are most prominent in the sand and silt fractions. Other minerals, such as the silicate clays and iron oxides, have been formed by the weathering of less resistant minerals as soil formation progressed. These minerals are called secondary minerals and tend to dominate the clay and in some cases the silt fraction.

The inorganic fraction of the soil is the original source of most of the mineral elements that are essential for plant growth. Although most of these elements are held within the crystalline structure of the minerals, a small but significant proportion is in the form of charged ions on the surface of the fine mineral particles, i.e. colloidal clays, and fine organic matter particles. These ions can be exchanged with ions in the soil solution, which are in turn then available for uptake by the roots of crop plants. These cation exchange reactions are among the most important mechanisms in enhancing the growth and development of plants.

The arrangement of the sand, silt and clay particles, i.e. the extent and manner in which they are bound to each other, is defined as the soil structure. This contrasts with soil texture, which is defined as the proportion of these particles in a soil. The particles may remain relatively independent of each other, but more commonly they are found associated together in aggregates. These aggregates are very important in influencing water and air movement through the soil pores. They also have an important influence in determining soil strength. In turn all of these factors have a major influence on plant growth. Soil aggregation is one of the prime soil properties affected by soil tillage and cultivation techniques, and its management is one of the prime objectives of tillage.

B. Soil Organic Matter

Soil organic matter is derived from plant and animal residues from the surface that have been incorporated into the soil by earthworms and other animals, and which are then further modified by microorganisms in the soil. Soil organic matter is continually being broken down and resynthesized by soil microbes and consequently is transitory in nature, lasting from a few hours to several hundred years. Regular inputs of plant residues are therefore required to maintain organic matter in the soil. The combined components that make up soil organic matter are known as humus. It is usually black or brown in colour and is very fine and exhibits colloidal properties.

Although organic matter only makes up 1 to 6 % of a well-drained mineral topsoil, and less in the subsoil layers, it has a major influence on soil properties and hence on plant growth. Organic matter binds mineral particles into aggregates that increases soil pore space and so promotes good water infiltration, holding and drainage characteristics. It is also a major source of some of the essential elements for plant growth, namely, phosphorus and sulphur, and a primary source of nitrogen. Organic matter is also the main source of energy for soil organisms and it thus drives the biochemical activity in the soil. Due to its light weight and colloidal properties, its capacity to hold water and nutrient ions greatly exceeds that of colloidal clay. Small amounts of humus thus markedly increase the soil’s capacity to promote plant growth.

The amount of organic matter in cultivated soil is heavily influenced by the tillage and crop management systems used, especially in arid regions. Due to this, and the importance of soil organic matter for crop growth, the management of soil organic matter is one of the prime considerations when selecting tillage and crop management systems.

C. Soil Water and Soil Air

The pore spaces between the individual solid soil particles and between the aggregates
of the solid soil particles are filled with water and air. Obviously, the proportion of air in the pore spaces is inversely proportional to the proportion of water in the pore spaces. Under conditions of optimum plant growth roughly half of the pore space is filled with water.

Water fulfils two essential roles for plant growth. Firstly, it is one of the main essential elements in the photosynthetic process. Secondly, together with its soluble constituents, including nutrient elements, such as calcium, potassium, nitrogen and phosphorus, it makes up the soil solution, which is the critical medium for supplying nutrients to growing plants. As described previously, nutrient ions on the colloidal clay and humus particles are exchanged with others in the plant roots through the soil solution.

When there is ample water in the large and intermediate-sized pores then water can move in any direction in the soil; it can drain downwards under gravity, move upwards to replace moisture lost through evaporation, and in any direction towards plant roots as they absorb water. When water is lost from the soil it drains out of the larger pores first, followed by that from the progressively smaller pores.

Not all the soil water is available to plants as there are strong attractive forces between the soil particles and the water. Depending on the soil, as much as one fourth to two thirds of the moisture may remain in the soil after the plants have wilted or died for lack of water.

The availability of air within the soil, and the free transfusion of gasses between the soil and the atmosphere, is important for optimum growth and especially for the germination of seeds. Some gasses within soil air are consumed by plant roots and by microbial reactions and other gasses are released. Due to this, and the close contact between soil air and soil water, soil air differs from atmospheric air in several respects. Firstly, the levels of carbon dioxide in soil air may be several hundred times higher than the 0.03% concentration commonly found in the atmosphere. Secondly, soil air generally has a higher moisture content than the atmosphere. Thirdly, the distribution of gasses within soil air is less uniform than in the atmosphere.

The movement of water and air into and through the soil in cultivated lands is to a large extent governed by the soil structure and hence heavily influenced by the tillage systems and crop management systems used.

2.1.1.2. The Formation of Soil and Soil Horizons

Some of the processes involved in the formation of soil have been described in the previous sections that described the constituents of soils and how they combine to form soil. This section will view the soil and its formation as a large dynamic system in a field.

The unconsolidated material that overlies the bedrock is known as regolith. The soil forms the upper portion of this regolith, as shown in Figure ____ (@ Brady 1990, p 7, fig. 1.3). The regolith may have been formed from material that has weathered from the underlying rock, or it may have been transported from another location by the action of water, ice, wind or gravity, and then deposited over the bedrock or the material covering the bedrock. Consequently, the regolith varies greatly from place to place and need not reflect the mineral composition of the bedrock over which it is lying.

The upper 1 to 2 metre of the regolith, i.e. the soil, differs from the material below. It is higher in organic matter, due to the presence of plant roots and plant residues from the surface that have been incorporated into the soil by earthworms and other animals, and which are then further modified by microorganisms in the soil. The upper layers are also more subject to weathering than lower layers. The vertical movement of water through the upper layers also carries some of the smaller soil particles with it and these are frequently deposited in specific
Brady (1990) lists three processes leading to the formation of soil:

a. Weathering and organic matter breakdown, by which some soil constituents are modified or destroyed and others are synthesised.

b. Translocation of inorganic and organic materials up and down the soil profile, the materials being moved mostly by water but also by soil organisms.

c. Accumulation of soil materials in horizontal layers (horizons) in the soil profile, either as they are formed in place or translocated from above or below the zone of accumulation.

The above processes lead to the formation and layering of soil above the parent material, and a common sequence of horizons in an uncultivated soil is shown in Figure ___ (@ Brady, p 56, fig. 3.7). Five master soil horizons are recognised and are designated using the capital letters O, A, E, B and C. Subordinate layers or distinctions within these master horizons are designated by lower case letters. These are defined below, based on Brady (1990):

- **O Horizons:**
  Comprised of organic horizons that form above the mineral soil. They result from litter derived from dead plants and animals. O horizons usually occur in forested areas and are generally absent in grassland regions.

- **A Horizons:**
  These are the topmost mineral horizons. They contain a strong mixture of partially decomposed organic matter, which tends to give them a darker colour than that of the lower horizons.

- **E Horizons:**
  The horizons from which maximum leaching have occurred of clay, iron and aluminium oxides. This leaves a concentration of resistant minerals, such as quartz, in the sand and silt sizes. An E horizon is generally lighter in colour than the A horizon and is found under the A horizon.

- **B Horizons:**
  The B horizons include layers in which the accumulation of materials transported from above and even from below has occurred. In humid regions, the B horizons are layers of maximum accumulation of materials such as iron and aluminium oxides and silicate clays. In arid and semi-arid regions, calcium carbonate, calcium sulphate, and other salts may accumulate in the B horizon.

- **C Horizon:**
  The C horizon is the unconsolidated material underlying the solum, or soil, i.e. horizons A and B. It may or may not be the same as the parent material from which the solum is formed. The C horizon is outside the zones of major biological activities and is generally little affected by the processes that formed the horizons above it. Its upper layers may in time become a part of the solum as weathering and erosion continue.

- **R Layers:**
  Underlying consolidated rock, with little evidence of weathering.

- **Transition Horizons:**
  These horizons are transitional between the master horizons (O, A, E, B and C). They may be dominated by properties of one horizon but have prominent characteristics of another. The letters of both horizons are used to designate the transition horizons (e.g. AE, EB, BE and BC), the dominant horizon being listed before the subordinate one. Letter combinations such as E/B are used to designate transition horizons where distinct parts of the horizon have properties of E and other parts have properties of B.

- **Subordinate Distinctions:**
  Master horizons are further characterised by specific properties such as distinctive colour or the accumulation of materials such as clays and salts. These subordinate distinctions are identified by using lower case letters that designate specific
characteristics, see Figure ___ (@ Brady 1990, p 58, Table 3.1). By illustration, a Bt horizon is a B horizon characterised by clay accumulation; likewise, in a Bk horizon carbonates have accumulated.

The above sequence was given as an illustration by Brady (1990) and as he points out, it is unlikely that all the horizons shown here will be found in any one particular soil. The ones most commonly found in well-drained soils are Oe, or Oa if the land is forested; A or E, or both, depending on circumstances; B or Bw; and C. The conditions leading to the formation of the soil will determine which others are present and their clarity of definition.

Tillage operations that mix the soil destroy the layered condition of the cultivated topsoil and produce a more or less homogeneous layer. In tillage the term topsoil refers to the plough layer or tilled layer, and the term subsoil refers to the soil below the tilled layer. These terms do not refer to specific horizons. The number of horizons affected by tillage is dependent both on the depth of tillage as well as on the depth of the horizons. In some soils the A and E horizons are deeper than the tillage depth, see Figure ____ (@ Brady p 58, fig. 3.8). In other cases where the upper horizons are shallow the tillage depth may be at the top of or even down into the B horizon.

Where erosion has washed away some of the top horizons the profile is said to be truncated. On cultivated land subject to long-term erosion, the maintenance of a constant tillage depth leads to tillage moving deeper into the soil profile. As Brady (1990) points out, many farmers are today cultivating the B horizons.

2.1.1.3. The Classification of Soils

Using some of the characteristics of soils described so far, such as soil depth, clay and humus content and degree of horizon development, to compare a body of soil in one specific location with that in another, it will be found that the two soils are markedly different, or markedly similar, or somewhere in between. This leads to the concept of individual soils, i.e. soils that exhibit a specific combination of characteristics common only to themselves, and this makes it possible to name and classify them. Historically, a major step in this field was taken at the end of the last century when researchers in Russia noted the relationship between climate, vegetation and soil characteristics, and this led to the concept of soils as natural bodies. A soil classification system based on this principle was then developed in the USA in the 1920's, and this has since been further developed.

Soil classification is necessary in order to study and use soils effectively. Soil properties may vary substantially from one soil type to another and these properties may crucially affect the outcome of an agricultural trial on a particular soil type. The use of a soil classification system assists greatly in analysing the results of the trial, and also in determining the transferability of those results to similar or dissimilar soil types.

Only a very brief discussion of some aspects of classification systems will be given here as it is beyond the scope of this publication to cover this area in detail. This subject is covered in detail in Brady (1990). Several different classification systems are used; the most common being "Soil Taxonomy (Soil Survey Staff, 1975)", used in the USA and many other countries;

The smallest three-dimensional unit of soil studied in a field is called a pedon (from the Greek, meaning ground), and it varies in size from about 1 to 10 m². This is too small a unit on which to base a field soil classification system, and so this is based on a group of pedons which are closely associated in a field and which exhibit similar properties, and this is termed a ploypedon and can be considered to be a soil individual. In the USA these approximate to what is called a soil series, of which 17000 have been characterised.
As Brady (1990) points out, the soil classification procedure described in "Soil Taxonomy" is based on the properties of soils as they are found today. In this system soil genesis is not ignored as it is usually reflected in the soil properties. A large number of the physical, chemical and biological properties of soils are used as criteria in the classification system. These include moisture, temperature, colour, texture, and structure of the soil. Chemical and mineral properties such as the contents of organic matter, clay, iron, and aluminium oxides, silicate clays, salts, the pH, and the percentage base saturation. Soil depth and the presence or absence of certain diagnostic soil horizons also determines the place of a soil in the classification system.

Using the soil classification system the soils are surveyed and mapped. Mapping units are initially outlined on aerial photographs and these are followed up by surveys in the field to verify the boundaries and identify the soil series. New techniques are being used to improve the quality and speed up the process. These include the use of video image analysis and ground penetrating radar. Soil maps are usually accompanied by a bulletin containing a description of the topography, climate, agriculture, and soils of the area under consideration. Suggestions for practical management of the soil are also usually made.

From the foregoing it can be seen that knowing the soil series in a field provides a wealth of information about that soil. Extension workers and agricultural agents often base their recommendations for land use and crop management on the soil surveys and the interpretative bulletins based on them. The soil survey is perhaps of greatest practical value in land classification for agricultural and other uses.

2.1.2. Soil Physical Properties

The soil physical properties which most affect crop growth, i.e. germination and root and shoot development, include the soils' strength and porosity characteristics, and its water, aeration and temperature conditions. None of these properties are independent variables and the modification of one may result in a change in the others. All of the soil physical properties are largely dependent on the soil texture and structure and this will be discussed firstly in detail.

2.1.2.1. Soil Texture and Structure.

Soil is composed of individual mineral and organic matter particles together with aggregates of these particles bonded to each other, with spaces called pores between these solid particles containing air and water. The sizes of the individual mineral particles vary greatly and these have been divided into three basic categories, viz; sands, silts and clays with the following size ranges, based on the Wentworth scale used in the USA:

- **Sand**
  - Coarse: 0.25 mm to 2 mm
  - Fine: 0.0625 mm to 0.25 mm
- **Silt**: .004 mm to .0625 mm
- **Clay**: less than .004 mm

The properties of a specific soil depend to a large extent on the relative proportions of the sand, silt and clay particles that make up that soil. Because of the importance of this, soils are classified into various textural classes as shown in Figure (Figure 2.1.)

To assist in understanding this diagram and its use several examples are given. In the triangular diagram the co-ordinates are the percentage sand, silt and clay, shown along the outer lines of the triangle. The 100% silt point with no sand and no clay is the right apex of the triangle.
triangle. If you move from there towards the left along the bottom of the triangle to the 10% sand point there will be 10% sand, 90% silt and 0% clay. For any point within the triangle the percent clay fraction is obtained by drawing a line through the point parallel to the base opposite to the clay apex, i.e. a horizontal line, to the percent clay scale. Similarly the percent silt fraction is obtained by drawing a line through the point parallel to the base opposite the silt apex to the percent silt scale. The percent sand fraction is obtained by drawing a line through the point parallel to the base opposite the sand apex to the percent sand scale. Obviously the total of the percentage components of a soil must add up to 100%.

The boundaries between the various classes are shown in heavy line. For example, from the diagram it can be seen that the boundaries of the silt class are, silt not less than roughly 88%, sand not more than 20% and, clay not more than roughly 12%. Another example is that a soil consisting of roughly 23% sand, 53% silt and 23% clay would be represented by point A on the diagram and would be classed as a silt loam.

Broader groupings of these textural classes have also been made. Coarse textured soils include sands, loamy sands and sandy loams except very fine sandy loams. Fine textured soils include clays, sandy clays, silty clays, clay loams, sandy clay loams, and silty clay loams. These Classes may be divided into fine, medium and coarse subclasses according to the size of the sand or clay fraction. Coarse textured soils are also referred to as "light" soils in reference to their usual ease of cultivation and conversely the term "heavy" soils is used to describe clay soils.

Some general points about the main classes are made below:

Sands: These include all soils in which the sand separates make up at least 70% and the clay separates 15% or less of the material by weight. The properties of these soils are typically those of sand as opposed to the adhesive nature of clays. Two specific textural classes are recognised, viz. sand and loamy sand, however, as can be seen from Table ____ (@ Brady p 96, table 4.2.) two additional subclasses are also used; loamy fine sand and loamy very fine sand.

Silts: The silt group is made up of silt not less than 80% and clay not more than 12%. Only one textural class, i.e. silt, is recognised.

Clays: A clayey soil includes those soils that contain not less than 40% of the clay separate, and in some cases those which contain not less than 35%. Although the characteristics of all these soils are dominated by the clay separate, some may contain more sand or silt than clay. Three specific textural classes are recognised, viz. clay, sandy clay and silty clay.

Loams: An ideal loam may be defined as a mixture of sand, silt and clay particles that exhibit the properties of those separates in about equal proportions. Most soils of agricultural importance are loams and the group contains many subdivisions.

The particle size distribution of a soil, i.e. the percentage sand, silt and clay it is made up of, is obtained by sifting the soil through a series of layered sieves of graduated sizes. To do this the soil is soaked in water and the aggregates are broken down chemically or mechanically prior to flushing them through the series of sieves. The soil particles collected in each of the graduated sieves are then dried and weighed to give the particle size distribution.

When the particle size distribution is not available from laboratory analysis the textural class of the soil can be roughly assessed from the feel of the moist soil. Figure____ (@ Godwin 1990, p 9, fig. 2.2) is a flow chart showing the procedure for assessing the textural class of a moist soil. To assess the texture of a soil take a handful of soil and, if dry, wet it gradually and kneed thoroughly between finger and thumb to break down any aggregates. Enough moisture
is needed to hold the soil together and for the soil to exhibit its maximum cohesion. Grittiness indicates a preponderance of sand, a silky soapy feel indicates a preponderance of silt, and stickiness indicates a preponderance of clay. A soil that is neither predominantly gritty, silky nor sticky is a loam.

Some of the individual soil particles are bound together by organic matter, inorganic salts and water into secondary particles, called peds or more commonly soil aggregates. The structural characteristics of a soil are determined by the aggregation of individual soil particles. The shape and packing together of the individual particles and the aggregates leaves spaces between the solid particles called voids or, more commonly, pores. The spaces between the solid particles within aggregates are very small, as the particles are bonded together, and the spaces are called micropores. The spaces between the aggregates are called macropores. Clay soils have a much greater ability to form aggregates than do sandy soils. As will be discussed later, the presence of soil organic matter is very important to promote aggregation. In sandy soils the presence of soil organic matter also helps to separate the sand particles and to prevent them from packing too closely together. See Figure____ (McKyes 1985, p 114, Fig. 5.9, plus Elwell (1989) p 35 Conservation Tillage).

Pore size is dependant on soil texture (individual particle size and preponderance of different sizes), soil structure (soil aggregate size and shape and preponderance of different sizes), soil density and crack and channel development. Based on the above several useful soil parameters can be defined:

**Bulk Density:** The ratio of the soil mass to its total volume. Units: kg/m$^3$.

**Porosity:** The ratio of the pore space to the total soil volume.

**Pore Size Distribution:** The proportions of the various pore sizes within the total pore space, which range from micropores to large voids. This is a function of the shapes and sizes of particles and aggregates forming the soil matrix.

Soil structure is often described in terms of the size, shape and strength of the aggregates, or the size, shape and stability of the pores. The different types of aggregates found in soils are shown in Figure ____ (Godwin 1990, p 11, fig. 2.3). The larger aggregates are frequently classified as coarse, with the others as medium or fine. When the aggregates have sharp edges they are termed angular and when the edges are rounded, sub-angular. Sub-angular structures have more large pores than angular ones. The number of larger pores tends to increase as the aggregates change from prismatic through blocky to granular and crumb in a soil of the same texture.

Soil aggregates that are stable in water are known as water stable aggregates. The stability of the aggregates when wet is an extremely desirable characteristic as this gives the soil resistance to compaction when moist. This reduces the tendency of loosened soil to compact under its own weight when wetted and also reduces soil compaction under animal or mechanical traffic on the surface. Furthermore, and possibly more importantly, the disintegration of the soil aggregates on the surface under the impact of raindrops, which leads to an increased risk of erosion, is also substantially reduced if the aggregates are water stable. The strength of the soil aggregates, and hence the stability of the pores, is very dependent on soil organic matter content and this will be dealt with in a later section.

Whereas clay soils can exhibit good aggregation, sandy soils are generally poorly aggregated even when soil organic matter levels are high. In sandy soils aggregates are generally only formed in tilled soils when the clay content is higher than 8% and when there is a suitable amount of soil organic matter (Harper and Brensing 1950). However, soil organic matter still plays a very important role in improving the structure of sandy soils by spacing out
the sand particles, and hence increasing porosity and reducing bulk density. A simple test to determine how good the structure of a soil is, for both clay soils and sandy soils, is given at the end of Section 2.1.3.4.

Some of the main factors that affect crop response are soil water, soil aeration, soil temperature and soil impedance to root growth. All of these factors are altered primarily by altering the structural properties of the soil and this is the most common immediate objective of tillage. Tillage operations do this generally by cutting and breaking up the soil and thus forming or breaking aggregates and so changing pore size distribution and porosity. The stability of these changes to the soil aggregates over time, i.e. following rainfall, traffic on the soil surface, etc., is crucial in determining the effectiveness and efficiency of the tillage operations. The establishment and maintenance of a good soil structure is a prime objective of most tillage systems.

2.1.2.2. Soil Water

Soil water is held within the pores of a soil, and flows through these pores. There are strong attractive forces between the soil particles and the water particles, and these forces determine the amount of water that can drain through the soil and the amount that is retained within the soil. When water is free to drain through a soil under the influence of gravity, the water will empty out of the larger pores first, followed by that from the progressively smaller pores. This continues until the point is reached where the forces holding the water to the soil equals the force being exerted by gravity on the water and no more water drains out. The water within the smaller pores, and especially the micropores within the soil aggregates, is strongly bound to the soil and is retained in a thin film around and between the soil particles and aggregates. Below a certain water content in the soil it is not possible for plants to extract that water from the soil because it is so strongly bound to the soil.

Based on the above the following definitions are made:

Saturated Soil: The total pore space within the soil is filled with water.

Field Capacity: The amount of water held in a soil at the equilibrium point when the force of gravity acting on the water equals the soil attractive forces, i.e., the maximum amount of water that can be retained in a soil without excess water draining through it. Units: mm/m depth of root zone.

Permanent Wilting Point: The water level within the soil below which a plant cannot extract the water due to the strong attractive forces between the soil and the water particles. Units: mm/m depth of root zone.

Plant Available Water: The water in the soil available to the plants between field capacity and permanent wilting point. Units: mm/m depth of root zone.

Moisture Deficiency: Level of water deficiency below field capacity. Units: mm/m depth of root zone.

Figure ___(@ Godwin 1990, p 18, fig. 2.8) shows the variation of these parameters with soil type. It will be noted that although clay has the highest field capacity, the amount of plant available water for clay is similar to that for a fine sand. The maximum plant available water occurs in a light clay loam or silt loam. Soils with low levels of plant available water are more susceptible to water limitations, when under short-term drought conditions, than soils with
high levels of plant available moisture.

An in-field method is available to estimate the soil moisture content of a soil without the use of instruments, and this is shown in Table ___(@ Godwin 1990, p 19, table 2.1). At moisture contents above field capacity “free” water is apparent for all soil texture classes. As the moisture deficit increases then other characteristics, as described in the table, are used to estimate the moisture deficiency.

The factors affecting the flow of water through the soil, i.e. its hydraulic conductivity, are the porosity, the pore size distribution, and the geometry and continuity of the soil pores. These factors are largely controlled by the textural class of the soil, its bulk density and the tillage practices it has been subjected to. Under saturated conditions the hydraulic conductivity of a soil increases as its porosity, fracturing and aggregation increases. However, under unsaturated conditions, the hydraulic conductivity decreases below a certain moisture deficiency level as the soil aggregate size increases, because the contact between water contained in different pores is reduced.

The textural class of a soil has a major influence on its hydraulic conductivity as does its bulk density. For example beach sand has a saturated hydraulic conductivity of .05 cm/s at a dry density of 1.4 t/m$^3$ and this is reduced to .02 cm/s at 1.66 t/m$^3$. At the other extreme some silts have a hydraulic conductivity of only .00006 cm/s at a dry density of 1.43 t/m$^3$ and this is reduced to .0000006 cm/s at 1.66 t/m$^3$.

2.1.2.3. Water Infiltration

Water falling onto the soil surface either infiltrates into the soil surface, or is retained on the surface, or flows down the slope as runoff. See Figure ____(@ Elwell 1989, p 38). The control of water infiltration in arid and semi-arid regions is one of the most important criteria in the selection of tillage systems. In these areas it is almost invariably desirable to minimise runoff and to maximise water infiltration. This is not only to maximise the amount of water available to the crop but also to minimise erosion by reducing runoff. Under tropical and sub-tropical rainfall conditions the intensity of rainfall is also often high. Under the above conditions it is then important to maximise the rate of water infiltration and to retain any excess water on the surface, by minimising runoff, so as to lengthen the time available for the water to infiltrate the soil.

For an understanding of the mechanics of water infiltration it is important to differentiate between the rate of infiltration and the total amount of infiltration. The latter is determined by the rate of infiltration, which changes rapidly during a rainfall event, and the total amount of time that the water is falling on the surface or is retained on the surface. The rate of infiltration of water into the soil surface is largely determined by the soil's hydraulic conductivity and the soil's water content. Both of these change during rainfall. It should be remembered that the rate of infiltration only becomes a limiting factor when it is lower than the rate of precipitation.

The hydraulic conductivity of the surface layers is usually different from that of deeper layers. The impact of raindrops on the soil tends to break up soil aggregates on the surface. The fragments from these broken aggregates pack together, fill the surface soil pores and form a thin surface layer that is less permeable than the original surface. This results in a reduction in the rate of water infiltration soon after a rainfall event starts. In some soils this surface layer, or crust, becomes very hard, especially after drying, and although only a few millimetres thick it is highly impermeable to water. This characteristic is called capping or crusting.

The rate of water infiltration into the deeper layers also changes during the course of a rainfall event, providing the soil was not saturated to start with. Dry soil rapidly absorbs surface
water into its empty, i.e. air filled, pores and fractures. Once these have been filled the infiltration rate slows down as it is limited by the hydraulic conductivity of the soil. As mentioned previously, hydraulic conductivity increases under saturated conditions as the soil's porosity, fracturing and aggregation increases.

Figure ___ (@ Godwin 1990, p 22, fig. 2.9), shows the variation of water infiltration rate with time during a rainfall event. Graph A demonstrates how crop residues protect the soil surface and so prolong high infiltration rates, until these are limited by the subsurface layers becoming saturated. The protection afforded the surface is proportional to the amount of residues retained on the surface. Graph B demonstrates how tillage operations such as ripping and chiselling increase the infiltration rate compared to no tillage with no crop residues retained on the surface by increasing porosity and opening up channels between the surface and lower soil layers. From the above it can also be deduced that if precipitation starts while the soil is still saturated then the infiltration rate will be low. If the rate of precipitation is high then runoff is likely to occur.

The most effective means of reducing capping, and the resultant decrease in the rate of water infiltration during precipitation is to retain adequate amounts of crop residues on the surface to intercept the raindrops before they impact on the soil surface. Shallow tillage operations can also be carried out shortly after rainfall to break the crust prior to the next rainfall, however, this still results in reduced rates of infiltration during the first rainfall event.

To increase the hydraulic conductivity of the lower surface layers and hence increase the rate of water infiltration, as well as to prolong the time for which the rate remains high, tillage operations which increase the soil's porosity, fracturing and aggregation should be chosen.

Tillage operations such as chiselling and ripping, fracture the soil, open large channels between the surface and lower layers and increase the pore size, thus increasing infiltration in well structured soils. However, in soils with a poor structural stability, excessive tillage may reduce aggregate size and porosity and thus reduce infiltration. Tillage operations also generally result in moisture loss and speed up the decomposition of soil organic matter, which is an essential component of water stable aggregates, and so may not be desirable. Furthermore, in soils where bio-channels exist from the activity of earthworms or termites, tillage may reduce infiltration by disrupting these channels. Increasing the depth of tillage also generally increases the capacity of the soil to absorb and retain water, however, because of energy considerations, tillage, if used, should be no deeper than necessary to reduce runoff to tolerable levels.

For the same rate of water infiltration, the total water infiltration can be increased by retaining the water on the soil surface where it falls for a longer period, so as to allow more time for infiltration to occur. This obviously also reduces the amount of runoff. Several methods can be used to achieve this, namely:

- Increasing surface roughness: By either selecting tillage operations that leave large soil clods on the surface, or by leaving crop residues on the surface.
- Forming small water retaining structures on the surface, such as:
  - Ridging slightly off-contour. When runoff occurs it flows down a much shallower gradient than the slope of the field, hence the rate of flow is slower. This both reduces the erosive force of the water and gives more time for the water to infiltrate. Planting is usually carried out on the top of the ridges, but is also done in the furrows in arid areas. Furthermore the furrows can be dammed, (or ridges tied), to retain the water where it falls. The dams are constructed to roughly half the height of the ridges so that they can overflow before the ridges.
  - Pot-holing. This operation involves scooping out holes in between the plant rows to retain water.
As will be noted above the presence of crop residues on the surface both reduces runoff and also increases the rate of infiltration. It does this by retaining water on the surface by in effect increasing surface roughness, and by also protecting the surface from raindrop impact and so limiting the build up of a thin layer on the surface with low hydraulic conductivity. The combination of both retaining water on the surface for a longer time as well as maintaining high infiltration rates into the top soil layers results in high levels of total water infiltration. This is one of the most important reasons for the retention of crop residues on the soil surface, and why they play such an important part in conservation tillage systems.

The amount of crop residue on the surface is of crucial importance in determining its effectiveness in protecting the soil aggregates on the surface. Table (Godwin 1990, p 21, table 2.2), shows the relationship between the amounts of residue retained on the surface and the resultant runoff, total infiltration and soil loss. It will be noted that small amounts of crop residue did not have a major effect on runoff or total infiltration, but did substantially reduce soil loss. Generally at least 30% of the soil surface area needs to be covered by crop residues for it to be effective in terms of soil and water conservation. This aspect is covered in Section 2.2.1.3. and details of the amount of crop residues left on the surface following various tillage operations are also given. It should also be noted that different crops vary in the level of cover they give when used as crop residues and further details of this are also given in the above section.

2.1.2.4. Soil Water Evaporation

Control of soil water evaporation is of almost equal importance to the control of water infiltration in arid and semi-arid farming areas. In most of these areas the mean daily open pan evaporation of water is greater than the mean daily precipitation even during the rainy season. The control of soil water evaporation therefore has a major affect on the availability of water to a growing crop and on the storage of water for a later crop.

Some fallow farming systems are a special case in which the conservation of moisture is the main objective of the tillage system. These systems are used in some arid and semi-arid areas to build up reserves of soil water during one rainy season, and these reserves are then either used to grow a crop during the cooler dry season, or otherwise used to supplement the rain during the next rainy season when the crop is grown. Post harvest tillage operations are also frequently designed to maintain soil moisture levels as high as possible prior to the start of the next cropping season.

Two main factors affect the rate of evaporation from a standing body of water and these will be briefly covered before passing onto evaporation of water from the soil:

- Heat/Energy: As the temperature of the water surface increases so more energy is available to agitate the water molecules and so provide the momentum for them to break through the water surface and be converted into vapour. A large amount of heat is required to convert water from its liquid to vapour stage. Over 500 times as much heat is required to convert a given quantity of water from liquid to vapour than is needed to raise the temperature of an equal quantity of water by 1 deg. C.
- Vapour concentration gradient: The amount of water vapour in the air immediately above the water surface also control evaporation. As the amount of water vapour immediately above the surface increases so the rate of evaporation from the water decreases. When the air immediately above the water is saturated with water vapour then further evaporation from the water ceases. There is usually a decreasing water vapour concentration gradient above the water. The highest concentration of water vapour occurs immediately above the water surface and this decreases with height above the water. The general air humidity therefore affects the rate of evaporation directly. Wind speed also affects the rate of evaporation by mixing up the air column above the evaporating water, and hence reducing the water vapour concentration.
immediately above the water surface, thereby increasing evaporation.

The process of soil water evaporation involves the conversion of water, on the soil surface or within the soil, from its liquid to its vapour phase and then its transfer into the atmosphere. Considering a soil that is initially saturated with water on the surface, evaporation takes place in three stages, as illustrated in Figure (Godwin 1990, p 24, fig. 2.10).

- In Stage 1, with water on the surface, the condition of the soil has no effect on the rate of evaporation. The rate of evaporation is controlled by atmospheric conditions, i.e. solar radiation, air temperature, wind speed and air humidity, as described above.
- In Stage 2 the soil surface starts to dry. At this point the amount of water vapour that the surface air layer can absorb exceeds the amount of water that can be transmitted through the soil to the soil surface. The rate of evaporation drops markedly from that in Stage 1 and is limited by the unsaturated hydraulic conductivity of the surface layer of soil. The evaporation rate is also reduced as the dry surface layer insulates the underlying moist soil and because it also reflects more solar radiation than wet soil, which reduces the heat input to the water. As drying continues an increasing amount of the water transmitted to the surface is in the vapour phase and less in the liquid phase, which further reduces the evaporation rate.
- Stage 3 occurs when a deep dry surface layer has formed and all the water transmitted to the surface through this layer is in the vapour phase. Evaporation rates in this stage are very low. However if a dry spell lasts for a long time the total loss of water during this stage can be high.

The main potential for the control of soil water evaporation lies in the control of Stages 1 and 2, however Stage 3 can also be controlled to a limited extent. There are basically four ways in which soil water evaporation can be controlled, viz.:

a. Reduce the solar radiation incident on the soil surface: This reduces the amount of heat available to vapourise the soil water.

b. Reduce the heat transfer from the soil surface to lower layers: This reduces the amount of heat available to vapourise soil water at lower depths.

c. Reduce wind speed immediately above the soil surface: This reduces the mixing effect that the wind has on the air column, and hence on the gradient of water vapour concentration above the soil. This leaves a higher concentration of water vapour immediately above the soil surface, than would be left if the wind speed was higher. This reduces the absorption of water vapour into the atmosphere at the soil surface.

d. Increase the resistance to water vapour flow between the point of evaporation and the atmosphere: This increases the concentration of water vapour at the point of evaporation and hence reduces evaporation.

The retention of crop residues on the soil surface reduces soil water evaporation, both by reducing solar radiation incident on the soil surface and by reducing the wind speed immediately above the soil surface, i.e. by the means described in a. and c. above. Crop residues are usually much lighter in colour than soil and so reflect a greater proportion of the incoming radiation than does soil. This reduces the heat entering the soil and hence energy available to vapourise the water. The crop residues on the surface also roughen the soil surface and so slow the wind speed down at the air/soil surface interface. This reduces the transfer of water vapour from the soil to the atmosphere.

The effectiveness of the use of surface crop residues to reduce evaporation is dependent both on the amount of residues left on the surface and on the length of the dry spells. Figure (Godwin 1990, p 25, fig 2.11), shows the daily change in the evaporation rate with time for various amounts of crop residues. Increasing the amount of residues has a large effect on reducing the evaporative loss rates, but also increases the length of stage one evaporation. The total water evaporated is given by the area under each curve. From this it can be seen that even though surface residues reduce Stage 1 evaporation rates, cumulative evaporation during extended dry periods may equal the total loss from the bare soil. Thus,
under dryland conditions, where crop residues are low, the retention of residues on the soil surface to control evaporation may not be effective during the dry season. However, during the rainy season, when the dry spells are much shorter, even limited amounts of crop residues can be very effective in reducing water loss and enhancing water storage.

Shallow tillage is the other main means of controlling soil water evaporation. Tillage disrupts the capillary pore continuity between the surface and deeper soil layers. This reduces the ability of the drying surface layer to draw up moisture from the wetter lower layers and hence it dries quicker. This in turn terminates Stage 1 drying, during which evaporation is at its maximum, and also hastens the decline of the evaporation rate in Stage 2 drying. Shallow tillage also reduces the thermal conductivity of the surface layer, which reduces the amount of heat transferred to vapourise soil water at lower depths. Some form of tillage is generally required if evaporation is to be controlled during long dry spells.

The main factors that determine the effectiveness of tillage in controlling soil water evaporation are:

- The timing of the tillage operation.
- The coarseness, or tilth, of the tilled layer.
- The depth of tillage.

The effect of the time of the tillage operation after rainfall on the evaporative water loss is shown in Figure ___ (@ Godwin 1990, p 26, fig. 2.12). It can be seen that if tillage is to be used to control evaporation then the operation should be undertaken as soon as possible after initial wetting to achieve maximum effect. However, various other factors, such as the danger of soil compaction that increases with increasing moisture content, also need to be considered.

The effect of the coarseness of the tilled layer on controlling soil water evaporation losses is shown in Figure ___ (@ Godwin 1990, p 27, fig. 2.13). The results show that a fine tilth treatment, with an aggregate size of 2.5 mm, was very much better than the medium or coarse tilth treatments, with aggregate sizes of 25 and 50 mm respectively, in reducing evaporation. This is because a coarse or cloddy surface results in an increased surface area of exposure, and because of its highly porous characteristics, which offer lower resistance to water vapour transfer than do fine soil mulches. These latter effects of a coarse soil mulch outweigh any reduction in surface wind speed, and hence of Stage 1 drying, that they may induce and result in increased evaporation. It will be noted that for the given conditions of the experiment the medium and coarse tilth treatments only started to produce better results than the untilled treatment after 200 hours.

From the above it can be seen that the coarseness of a soil mulch will have a major effect on the water content of the seed zone during a long, dry period of high evaporative demand. Under these conditions more water is lost from the seed zone with a coarse mulch than a fine mulch, and this could result in poor seed germination and emergence.

The effectiveness of tillage to control evaporative losses is also dependent on soil texture. Tillage is more effective in reducing the hydraulic conductivity of clay soils than sandy soils. Substantial evaporative losses can occur in untilled, fine textured soils, for example in clays and clay loams, and tillage can be effectively used to control these losses. However, in coarse textured soils, evaporative water loss is often not markedly affected by tillage.

The choice of the depth of tillage to control evaporative losses is dependant on several factors. The deeper the tilled layer the more effective it is in insulating lower layers from surface heat and in controlling water and water vapour transfer from the lower layers. However, water loss from the tilled layer is speeded up by tillage, because moist soil is brought up to the surface and because the porosity of the tilled layer is increased, thus allowing more rapid vapour loss from the tilled layer to the atmosphere. This is shown in Figure ___ (@ Godwin 1990, p 29, fig. 2.15).
For good moisture conditions in the seed zone it is also important that the seed zone soil water has good capillary continuity with deeper soil layers. During seedbed preparation the soil aggregate size aimed for is usually 1 to 5 mm in order to provide good seed/soil contact, and this is discussed further in Section 2.4.1.1. This aggregate size is similar to the size of the fine tilth used for evaporation control, and the tillage has to be below seed zone depth. As described above this results in moisture loss from the seed zone as well as a break in the capillary continuity with lower soil levels. However, the moisture levels and capillary continuity are restored during rainfall prior to planting. Furthermore, capillary continuity can be enhanced by slightly compacting the soil under the seed during the planting process.

The maximum depth that can be tilled for evaporation control is frequently limited by the depth of seed placement. Moisture retention at this level is critical for good seed germination and initial seedling growth. Once the plant is more mature it can abstract moisture from a much wider depth range. The optimum depth of soil mulch required is dependent both on soil texture and soil structure. Generally, fine textured soils (e.g. clays, clay loams) require a greater mulch thickness than coarse textured soils (e.g. sands, sandy loams). This is because fine textured soils generally aggregate more and hence have a higher porosity, especially when newly tilled. This in turn means that a deeper mulch thickness is required to provide better resistance to water vapour movement. When precipitation restores liquid continuity through the tilled layer and a dry period follows, then tillage should be performed to re-establish the soil mulch to reduce water loss. As the loosened layer will over a short period of time dry out completely, the use of shallow tillage to control evaporation is effective only when the depth of soil moistened is substantially deeper than the depth of tillage.

Two important points of caution need to be raised at this point. Firstly, in regions where there is a high evaporative demand during the rainy season then tillage can be detrimental to water conservation. This follows from tillage increasing the water storage capacity of the shallow soil layers because it increases the soil's porosity. Because of the increased porosity and high percentage of large pores, the water content of a shallow tilled soil layer must be near or at saturation before water will penetrate into deeper soil layers. When rainfall does not wet through the tilled layer, water is held in it near the surface from where it can readily evaporate.

Secondly, although a fine soil mulch is better at reducing soil water evaporation than a coarse soil, the latter will allow a higher rate of water infiltration than a fine soil mulch. Furthermore a coarse mulch is less prone to wind and water erosion than a fine mulch. A balance between these factors needs to be made depending on the expected climatic conditions. One tillage system that does meet some of these contradictory requirements is stubble-mulching, a combination of shallow tillage and the retention of crop residues. This system both reduces the erosion hazard and also combines the advantages of tillage and residue retention in reducing evaporative water loss.

Where relatively deep tillage is used, i.e. below the seed zone, the initial operations should be the deepest, and then subsequent tillage should be progressively shallower so that a firm, moist seedbed is available at crop planting time. The effect of the depth of tillage on yield through its effect on soil water content is discussed further in Sections 2.4.5 and 2.4.1.1.

2.1.2.5. Soil Aeration

Soil aeration involves the exchange of gasses, primarily oxygen and carbon dioxide, between the soil and the atmosphere. Poor aeration can lead to a build up of carbon dioxide in the soil that inhibits seed germination. This is usually only a problem in humid areas, but can be a problem in areas of low rainfall on poorly drained clay soils and in soils that are prone to crusting.
Gas exchange is primarily by means of gas diffusion through the soil pores and this is 10 000 times faster in air than in water. Hence the air-filled porosity of the soil is more important for aeration than the total porosity of the soil, as a large percentage of the pores may be filled with water. An air-filled porosity higher than 10% is needed to provide adequate aeration for most plants. Large and continuous soil pores promote adequate drainage and good air exchange. Generally air-filled porosity increases as aggregate size increases or bulk density decreases.

Where soil aeration is a problem due to poor drainage, one of the objectives of the tillage operations should be to improve drainage, by increasing aggregate size or reducing bulk density. This can be done by tillage operations that loosen the soil, without pulverising it, and which promote the retention of organic matter to strengthen soil aggregates. Where soil aeration is a problem due to dense surface layers, or surface capping, tillage operations can be used to break up these crusts prior to germination. Alternatively tillage systems can be selected which leave crop residues on the surface to reduce raindrop impact on the soil surface, as this is the mechanism by which the dense surface layers are formed.

### 2.1.2.6. Soil Thermal Properties

As discussed in the section on soil water evaporation, soil temperature is a major factor in determining the rate of evaporation of water from the soil. The manipulation of the soil temperature through the use of various tillage operations, or tillage systems, is an important means by which the moisture content of the soil can be controlled.

Soil temperature is determined by the amount of heat entering and leaving the soil and the thermal properties of the soil. The main source of heat entering the soil surface is solar radiation (sunlight). Only the radiation absorbed by the soil surface heats the soil. Solar radiation immediately reflected from the soil surface back into the atmosphere does not heat the soil. The main forms of heat loss from the soil surface are:

- Heat radiated from the surface into the atmosphere.
- Heat absorbed by evaporating soil water and lost to the atmosphere through vapour transfer.
- Heat from the surface layers lost to lower soil layers by heat conduction.

The thermal properties of the soil determine the extent to which the soil temperature changes for a given change in heat input. The thermal properties of interest are the specific heat capacity, and the thermal conductivity of the soil. These are defined below:

- **Specific Heat Capacity or Specific Heat:**
  The quantity of heat energy required to raise the temperature of 1 kg of a substance by 1 degree Centigrade. Units: Joules/(kg deg.C)

- **Thermal Conductivity:**
  The rate of heat flow through a surface, measured at right angles to the surface, per unit area per degree temperature gradient. Units: Watts/(m deg.C).

The main factor that affects the specific heat capacity of a soil is water content. Those that affect its thermal conductivity are water content, bulk density and the mean size of aggregates. The soil mineral content has little influence on either the specific heat capacity or thermal conductivity of a soil, and the influence of soil organic matter is fairly minor. Increasing levels of the latter decrease both the soil specific heat capacity and thermal conductivity.

The specific heat capacity of water is 4190 J/(kg deg.C), whereas that for most mineral soils is about 2000 J/(kg deg.C). Hence, as the water content of a soil increases so does its specific heat capacity and this relationship is linear. This means that for the same amount of heat applied to a soil, the temperature of that soil will rise less when it is wet than when it is dry. Hence, in areas where low temperatures restrict the start of the cropping season, and where
low soil moisture content is not a restraint, it is desirable to reduce the moisture level of the soil so as to speed up the warming of the soil.

Changes in bulk density affect the specific heat capacity of a soil through its effect on the water content of the soil. See Figure ____ (@ Godwin 1990, p 13, fig. 2.4) loosening the soil decreases bulk density, by increasing the pore space, and so increases the water holding capacity of the soil. Thus, following wetting, a loosened soil has a higher specific heat capacity than if it had not been loosened. (Note that in some papers the units of specific heat capacity of a soil are given in terms of volume rather than mass. If these units are used then changes in the bulk density of the soil directly affects specific heat capacity, even if the water content of the soil remains constant).

The thermal conductivity of a soil is much more sensitive than specific heat capacity to changes in the water content of the soil. Whereas an increase in water content increases the specific heat capacity of a soil two to four times, over the normal range of soil water content, the thermal conductivity can increase 100 times over the same moisture range. The transfer of heat within a soil occurs within the particles and aggregates and between them through their points of contact, as well as across the air filled and water filled pores. As the thermal conductivity of water is roughly 20 times greater than that of air, the thermal conductivity of the soil increases rapidly as water content increases. As can be seen from Figure ____ (@ Godwin 1990, p 13, fig. 2.4) the rate of change of thermal conductivity with water content is greatest at low water content values. Although thermal conductivity is higher in a wet soil than a dry soil, soil at greater depth will warm more slowly in a wet soil, due to its greater specific heat capacity.

The other prime factors that affect the thermal conductivity of a soil are bulk density and mean soil aggregate size. As mentioned previously the transfer of heat through a soil occurs within the particles and aggregates and between them through their points of contact, as well as across the air filled and water filled pores. The thermal conductivity of soil minerals is approximately 100 times greater than that of air and 5 times greater than that of water. Hence an increase in soil porosity, i.e. a decrease in bulk density, decreases thermal conductivity. The aggregate size also influences the thermal conductivity. The thermal conductivity of a soil decreases as the mean aggregate size increases because the number of contact points, and contact area decreases.

As mentioned previously the conservation of soil moisture is one of the prime objectives of tillage in arid and semi-arid farming areas. From the foregoing discussion, it would appear that the use of tillage practices to produce a soil mulch that is loose, coarse and dry would minimise thermal conductivity, and so minimise evaporation. However, this ignores the effects of the other factors discussed in the section on soil water evaporation. As shown there, a fine soil mulch is better at reducing water vapour transfer from the soil to the atmosphere than a coarse soil mulch, and this outweighs the effect of the reduction in thermal conductivity.

As the dry soil mulch acts as an insulation layer over the subsoil, it transmits, or looses, less heat to the subsoil and as a result the temperature of the surface mulch is increased. This in turn results in increased radiative and convective heat loss to the atmosphere. Because the dry surface mulch acts as an insulating layer, it also reduces heat loss from the subsoil at night or during cold periods. Therefore, tillage tends to reduce the heat uptake and heat loss of the subsoil, and causes more of the heat exchange to occur at the soil surface. Hence during daylight hours, soils near the surface, i.e. roughly 0 to 5 cm deep, are warmer when tilled and cooler when untilled. During night time the opposite occurs. Conversely the temperatures in the subsoils, i.e. roughly below 10 cm are generally at all times lower in tilled soil than in untilled soils. It should also be noted that there is a time lag between the maximum surface temperature and the maximum subsoil temperature, because of the time it takes for heat conduction to take place. Under cloudless conditions surface soil reaches its maximum temperature a couple of hours after midday, whereas soil at 25 cm depth reaches its maximum temperature a couple of hours after midday.
shortly before midnight.

Crop residues on the soil surface can act as a very good insulating layer and can be much more effective in this regard than soil mulches. Surface residues act as a thermal barrier by reflecting incoming radiation, reducing wind contact with the soil surface and reducing soil water evaporation. The effectiveness of residues as an insulator is largely dependent on the quantity left on the surface. Compared with bare soils, a crop residue mulch decreases the average soil temperature at all depths as the surface temperature increases, i.e. during the day or spring warm up. Conversely, as the surface temperature decreases during the night or during autumn, crop residue mulches maintain higher soil temperatures compared with bare soil.

Cultural practices such as soil ridging or row direction can also influence soil temperatures. Temperatures during the growing season are higher on the ridges and lower in the furrows than with a smooth surface. Ridging decreases the reflected solar radiation that increases the heat input to the soil surface. Consequently, the average temperature of ridged or cloddy fields is higher than those with a smooth surface. Crop row direction affects the amount of solar radiation that is incident upon the soil surface by altering crop shading. Soil temperatures are generally higher under east-west oriented ridges or rows than under other orientations during early spring.

2.1.2.7. Soil Strength and Compaction

The strength of a soil is important in relation to its load bearing capacity and its associated resistance to compaction; the resistant force it exerts on tillage implements; the tractive effort that can be applied to it; and the resistance it provides to root development. Low strength is desirable for ease of cultivation and root penetration, but high strength is desirable to resist compaction under machinery loading and to allow good traction. The principal factors that influence soil strength are soil moisture content, bulk density, texture (particle size), and organic matter content. Various tillage operations and systems can be selected to modify soil strength and to rectify compaction problems.

A. Soil Strength

Much of the analytical framework used to study strength in homogenous, ductile materials, such as metals, can be applied to soils. This is despite the fact that soil is not a homogeneous material, as it is granular and has pores. Furthermore, although the forces applied to a soil are applied over a finite area, the boundaries of the affected mass are semi-infinite. A brief summary of the basic terms and equations used for homogenous, ductile materials is given below in conjunction with Figure ____ (@ McKyes p 34, fig. 2.20). This information is also of use in the understanding of the forces applied to tillage implements.

- **Applied Force:**
  When an external force is applied to a material it causes a deformation of that material, the strain, which in turn sets up an internal force, the stress.

- **Stress:**
  Two components or forms of stress are defined which occur at right angles to each other:
  - **Direct Stress:**
    \[ s = \frac{F}{A} \]
    The external applied force acts at right angles to the plane in which the area is measured. The stress is either compressive or tensile. Units: N/m²
  - **Shear Stress:**
    \[ t = \frac{Q}{A} \]
    The external applied force acts in the same plane in which the area is measured.
Strain:
Two components or forms of strain are defined which occur at right angles to each other.
Direct Strain:
\[ e = \text{change in length } dl / \text{original length} \]
Units: Dimensionless
Shear Strain:
\[ y = \text{deformation } x / \text{original dimension } l \]
Units: Dimensionless

Elastic Limit, Plastic Limit, Yield Point:
If a force is applied to an object such that the strain is below the elastic limit and the force is then removed, then the object will return to its original shape. If the force is increased to a level between the elastic limit and the plastic limit and then removed, then, although deformation will decrease with decreasing applied force, some permanent deformation will remain even after the applied force is totally removed. Once the force is applied to a level beyond the plastic limit, then deformation will continue without an increase in applied force until failure occurs at the yield point.

The main ways in which the soil stress-strain behaviour differs from that of a ductile material is that the elastic limit is very low, i.e., soil can suffer irrecoverable yield after only small deformations, and it exhibits only small rebound of shear or volumetric strains.

Four types of failure for soil can be defined in terms of stress-strain behaviour, viz., shear, compression, tension, and plastic flow. As shear failure is usually an intrinsic component of the failure mechanism in compression, tension and plastic flow failure, and as there are problems in the analysis of the last three, shear failure is generally used to determining soil strength. In Figure ___ (@ McKyes 1985, p 14, fig. 2.4) it can be seen how compression forces acting at a point in a soil are factored into forces acting along the shear plane and normal to it.

Soil strength is the capacity of a particular soil in a particular condition to resist an applied force. Soil strength can also be defined as the capacity of a soil to withstand deformation when a force is applied to it. Strength is measured in terms of the maximum force per unit area that can be resisted.

The capacity of a soil to resist an applied force is due partly to cohesion and partly to frictional resistance. Cohesion is that force which bonds soil particles to each other. The frictional resistance is that force that occurs once the soil starts to deform and the soil particles start to rub against each other. This resistance occurs on a plane within the soil at an angle to the applied force, and is proportional to the force acting at right angles to that plane.

When a force much lower than the maximum force that can be resisted is applied the soil deforms slightly, but "springs" back to almost its original condition when the force is removed. However, if a force greater than the maximum force that can be resisted is applied, then the soil deforms permanently and does not retain its original condition even after the force is removed. When this occurs under a compressive force the soil particles are forced closer to each other and this is termed compaction.

The principal factors that influence soil strength are soil moisture content, bulk density, texture (particle size), and organic matter content, and these relationships are described below.

The strength of a soil decreases markedly as its moisture content increases. This is because the water reduces the cohesive forces holding the soil particles together, and also because it reduces the friction between soil particles as they move under the applied force. Due to the above, moist soils deform readily when a force is applied to them, for example under the compressive force of a tractor wheel. For this reason the moisture content of soils is
one of the most important criteria in determining when tillage operations can be carried out, and this will be discussed further later.

Sandy soils have a low cohesion component but a high frictional resistance, due to the granular nature of the sand particles. By contrast, pure clay soils have a high cohesion component but a low frictional resistance, due to the smooth plate-like shape of the clay particles. In general, coarser textured soils have higher soil strength than finer textured soils. However, dry, compacted soils with a high clay content have very high soils strengths making them difficult to till under these conditions. The strength of coarser textured soils is also less affected by their moisture content than that of finer textured soils, and this generally makes them easier to manage.

The strength of a soil increases as its bulk density increases. This is due mainly to an increase in the frictional resistance to movement, because interlocking between soil particles, aggregates and clods increases as bulk density increases. The other component of soil strength, cohesion, is not markedly affected by changes in bulk density. From the preceding paragraph it can also be seen that the strength of sandy soils is more affected by changes in bulk density than that of clay soils.

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The main effect of soil organic matter on soil strength is that it promotes the formation of soil aggregates. These improve resistance to deformation in soils by increasing the frictional resistance to movement. As soil organic matter increases the stability of soil aggregates when moist, it plays a very important role in increasing the strength of moist soils.

When a tillage implement cuts the soil the force exerted by the tool on the soil ahead of it results in mechanical failure along successive internal rupture surfaces, see Figure ___ (@ McKyes 1985, p 34, fig. 2.21). The resulting soil left behind the tool has a much higher porosity than the untilled soil, and this is usually the objective of these tillage operations.

For tillage operations that require a shattering effect for their successful implementation, e.g. ripping, it is essential that the soil is sufficiently dry to allow the formation of clean internal rupture surfaces. All tillage operations require the soil not to be so moist that deformation rather than shattering is the major effect. Deformation should be avoided as it destroys the soil structure and will result in smearing rather than increased aggregation and porosity.

B. The Causes and Control of Compaction

The most important aspect of soil strength for most extension work relates to compaction that results from the deformation of a soil under a vertical compressive load. The compaction of a soil can be defined as an increase in its dry density, or the associated closer packing of solid particles or reduction in porosity. Considering a compressive force acting on the soil surface, then from the foregoing it can be seen that the greater the strength of a soil, the less it will deform under an applied load. Deliberate compaction is used in some tillage operations, for example rolling of seedbeds. However, compaction is generally a harmful side effect of traffic passing over the soil and it can seriously restrict plant root development and infiltration. The hazard of soil compaction is generally much greater during tillage under moist than dry conditions. An important objective of good soil management is both to minimise and alleviate soil compaction.

From Figure ___ (@ Godwin 1990, p 34, fig. 2.21) it can be seen how the bulk density, at a constant moisture content, increases as the externally applied pressure increases. Hence, minimising the weight of equipment travelling over a field and the pressure that the equipment exerts on the soil surface, for example by reducing tractor tyre pressure to increase the area of the tyre, will minimise soil compaction.
From Figure ___ (@ Godwin 1990, p 34, fig. 2.20) it can be seen that the pressure, or force per unit area, required to compact a soil to a specific density decreases exponentially as the moisture content increases. It is therefore important that after wetting of the soil that no machinery that exerts a high load per unit area on the soil is taken into the field, until the moisture content of the soil has decreased to acceptable levels so as to avoid excessive compaction. This will be discussed further later in this section.

Compaction can result from natural causes, such as the impact of raindrops, soaking and then drying, internal water tension, etc. Compaction can also be caused artificially by the downward forces exerted by machinery or animals passing over the soil surface. These natural and artificial agents of compaction can produce compaction in several different forms:

- Surface crusting or capping: This is caused by raindrop impact on the surface breaking up the aggregates on the surface, with the soil particles forming a thin hard crust on the surface when they dry.
- Plough pans or hard impermeable layers at depth below the surface: Plough pans are hard impermeable layers, formed at the bottom of the plough furrow, both through the weight of the tractor wheels, when these are run in the open plough furrow, and from the downward acting forces of the plough smearing the bottom of the furrow, and by always ploughing to the same depth. Other hard impermeable layers can also be formed by the leaching of fine soil particles from the surface layers to accumulate at a lower layer.
- Compaction spread throughout a large volume: This is caused naturally by soaking and drying and artificially by the weight of vehicles or animals on the surface.

The deliberate compaction of soil is, however, used in seedbed preparation. This is carried out using rollers either before or after seeding to improve the seed/soil contact or to reduce the porosity of the surface layer to improve moisture conservation. The shape of the roller partly determines the depth to which compaction will occur. Rollers with small diameters and large surface areas compact the soil more shallowly than narrow wheels with large diameters. Spike rollers cause high pressures over small areas and are effective for compacting at greater depths, especially when moving at slow speeds.

Figure ___ (@ McKyes 1985, p 106, fig. 5.2), shows the distribution of the change in soil dry density following successive passes of a tractor and trailer over a sandy loam soil. It can be seen that not only does density increase with successive passes, but also that the depth and width of the soil affected by the changes also increases. It will also be noted that maximum density occurs below the soil surface.

When soil is compacted there is a re-arrangement of soil particles and a reduction in pore volume, particularly of the large pores. When a soil is dry, it resists compaction because of its high bonding or cohesive strength, and the high degree of particle interlocking and hence frictional resistance to deformation. As the water content increases, the bulk density under a given applied pressure increases because water reduces the inter-particle friction and also weakens the cohesion between particles. At water contents above the maximum compaction density, water fills the pore space as compaction proceeds and further compaction is resisted by water pressure. This is shown in Figure ___(@ McKyes 1985, p 107, fig. 5.3), where compaction from different levels of traffic in the field is shown for different moisture contents. For the soil under test it can be seen that maximum compaction occurred at around 15% moisture content and decreased at higher and lower moisture contents. The increase in soil density under the dry soil state, below 5% moisture content, was four to five times less than that at 15% moisture content. It will also be noted that at a moisture content of 30%, compaction was generally less than compaction at 5% moisture content. However, this does not mean that it is acceptable to take machinery into fields at high moisture contents, as the machinery will destroy the soil structure at the soil surface, even though it may lead to less severe compaction problems immediately below the surface. At high moisture contents clod
and aggregate shear strengths are low, even though the bulk shear strength may be acceptably high, see Figure ___(@ Krause, 1984, GTZ p 21, fig. 4), and shear forces from wheel pressure or slippage, or trampling by draught animals leads to the breakdown of the clods and aggregates on the surface. As mentioned previously this leads to surface crusting, infiltration problems and increased erosion hazards.

Four important factors, in addition to the various soil factors, which affect compaction from wheeled traffic, are listed below:

- The total load from the wheel acting on the soil surface: Increases in wheel load result in greater compaction at depth below the surface.
- The resultant load per unit area acting on the soil surface: Increases in ground pressure beneath the tyres result in greater compaction at the surface.
- The amount of wheel slippage. Excessive wheel slippage can result in twice the level of compaction for the same weight of vehicle.
- The number of passes: Most of the compaction takes place on the first pass with subsequent passes contributing less each time. This is because the soil strength increases due to compaction and so is more capable of supporting the weight of the vehicle with less deformation at each pass, providing moisture conditions remain constant.

To minimise compaction, during cultivating and harvesting, it is necessary to both reduce vehicle weight and to reduce ground pressure by increasing the tyre-soil contact area through the use of dual wheels or low pressure tyres. Krause et al (1984) point out that the tyre-soil contact pressure should be limited to less than 70 Kpa for a cultivation programme that requires five to ten passes of machines on the field per year. Wheel slippage should be limited to a maximum of 16%. It is also desirable to reduce the number of traffic passes over the soil by combining operations, or by the use of controlled traffic systems where successive passes of the tractor are limited to the same path.

Figure ___(@ Krause 1985, GTZ p 21, fig. 4) summarises some of the previous information in a generalised format and also outlines the limits in terms of moisture content for the soil's optimum workability and trafficability. Krause et al (1984) define these terms as follows:

- Workability is the soil's suitability for tillage or for facilitating tillage operations. The workability of a soil is good when this range is wide. When it is narrow, or commences at a level where the moisture content is much lower than the field capacity, then the workability is poor. This is because tillage then cannot start until the soil has dried for a considerable period after the rains.
- Trafficability is the soil's capacity to carry the weight of a tractor, or animal, and implement.

Optimum workability and trafficability may not always occur at the same time. For example, when drying conditions are strong, the topsoil may be dry enough for seedbed preparation, and hence workable, but the subsoil may be wet and prone to severe compaction, and so is not trafficable. The optimum workability and trafficability depends on the type of tillage and implements used. For example, for ploughing, the soil will have a much wider workability and trafficability range than for seedbed preparation.

Krause et al (1984) give as a general rule that optimum workability and trafficability occur when the moisture content is around 60% of field capacity. (Field capacity is the moisture content of an initially saturated soil, allowed to drain freely for 24 to 48 hours). When the moisture content does not drop to this value and tillage operations have to be carried out then tillage methods should be chosen which cause as little damage as possible to the soil.

The moisture content for specific operations may be considered optimum when either, the work input or power required to perform the operation is the least, or when the desired
Effect is the greatest. Generally these criteria do not coincide and a choice or compromise has to be made.

C. The Effects of Compaction on Crop Growth

Compaction can have a seriously detrimental effect on crop growth, through its effect on soil pore size and soil strength, as these are the primary factors controlling root penetration. Roots grow partly through existing pores and partly by moving soil aside. Under compacted soil conditions, the average pore size is reduced and roots must widen pores by exerting pressure greater than the soil strength. Some plants are more capable than others at penetrating compacted layers because of their smaller root tip diameters.

The effect of soil strength on root penetration is shown in Figure ___ (@ McKyes 1985, p 116, fig. 5.10). As can be seen, although roughly 50% of the cotton taproots penetrated the hard layer that had a cone penetration resistance of 0.9 Mpa, less than 10% penetrated the layer that had a cone penetration resistance of 1.5 Mpa. This effect can be seen in the field, if a hard plough pan has been formed, by digging down next to a plant and noting how the penetration of the roots is restricted by the hard pan. If a plant encounters a hard pan, or is surrounded by compacted soil, then its overall root growth will be stunted as will be its general vegetative growth. The plant will also be much more prone to water stress in times of water deficiency. This is because the existence of hard impermeable layers limits the depth to which roots can grow and hence extract water and nutrients from, as well as limits the volume of soil that can store water.

Depending on the depth and strength of the compacted layer it may be possible to use a deep rooting crop with strongly penetrating root systems to break through the layer. If the main crop to be grown does not have this attribute then a strongly rooting crop could be grown in the rotation. The advantage of using a crop to break the compacted layer rather a tillage operation is the saving in energy expenditure. However, this would need to be balanced against the cost or food penalty of growing the strongly rooted crop rather than the preferred crop. A table giving the rooting depths of crops and marking out the strongly rooting ones is given in Section 2.4.1.2.

Both the textural class of a soil and its bulk density determine its porosity and hence its penetrability by plant roots. Table ___ (@ Godwin 1990, p 38, table 2.5) gives the non-limiting, critical and root-limiting bulk densities for the soil textural classes.

A soil which is has too low a bulk density may also result in the reduced growth of a plant. This is because as bulk density decreases hydraulic conductivity increases, and this may result in a loose porous soil draining too quickly and storing insufficient water for the long dry periods common in semi-arid areas. This in turn would lead to sub-optimum growth. This situation leads to the concept of an optimum density for soil for the optimum growth of crops.

The optimum soil density is dependent on soil type, crop type and weather pattern. This is illustrated in Figure ___ (@ McKyes 1985, p 118, fig. 5.12). This figure also illustrates the caution that needs to borne in mind with this concept of optimum soil density. What is optimum for one soil type and one crop type in one year may not be suitable for another year. However, as in all agricultural production, it is the expected weather pattern that has to be planned for. In the figure it can be seen that the optimum soil density for 1976 was about 0.99 t/m$^3$ and that for the other two normal years was 1.13 t/m$^3$. The amount of rainfall in 1976 was much higher than in 1977 and 1980. This led to the plants in the plots with a lower soil density producing a higher dry matter yield in 1976 than the plots with higher soil densities. This was because the loose soil, which allowed higher water infiltration and easier plant root growth, allowed the plants to take advantage of the plentiful rainfall and to produce higher yields than normal. During normal years with long dry spells, plants in the low density soils were subjects to water stress and yields were suppressed.
The bulk density and the soil strength of the upper soil profiles are strongly influenced by different tillage practices. These are shown in Figure ___ (@ Godwin 1990, p 36, fig. 2.23). Tillage reduces soil strength by breaking the bonding between soil particles and decreases bulk density by increasing porosity.

D. The Rectification of Compaction Problems

The rectification of compaction problems is an important function of tillage operations, and various alternatives are listed below:

- **Hard surface crusts or capping:**
  - Maintain a moist soil surface during germination and emergence to reduce the strength of the surface layer.
  - Retain residue mulches on the surface to reduce crusting caused by raindrop impact, and to maintain moist surface by reducing drying.
  - Shallow tillage to promote water infiltration and, prior to emergence, to allow emergence of the petioles.

- **Plough pans or hard impermeable layers at depth:**
  - Fields should always be checked for the existence of plough pans before planning tillage operations. If they exist then they should be either deep ploughed or ripped, depending on depth. In subsequent ploughing operations the depth of ploughing should be alternated to reduce likelihood of their formation.
  - Deep rooting crops with strongly penetrating root systems can sometimes be used in a rotation to break through hard impermeable layers.

- **General compaction:**
  - Deep plough or rip to reduce soil strength. Identify source of compaction for future avoidance due to cost of rectification.
  - Increase organic matter content so as to increase aggregation as well as the strength of the aggregates when moist.

2.1.3. **Soil Organic Matter Properties**

The organic matter content of a soil, also called humus, has a major influence on a number of important soil properties, including; fertility, potential productivity, structure and resistance to erosion. Organic matter forms a very important component of soil aggregates and particularly of water stable soil aggregates. Organic matter has a high water holding capacity and this, in addition to its beneficial effect on soil structure through the improvement of soil aggregation, markedly increases the water holding capacity of soils, especially of sandy soils. These attributes lead to improved air and water relationships in the soil, and particularly to increased water infiltration and water storage. They also lead to improved root growth and resistance to compaction, and increased resistance to wind and water erosion. As organic matter decomposes it also provides a source of plant nutrients. Furthermore it has several properties that enhance the use of applied fertilizers to the soil. Organic matter also imparts a dark colour to soils that increases their capacity to absorb heat and warm up rapidly in the spring. However this last characteristic may be detrimental to soil water evaporation during hot periods.

Tillage has a major effect on the organic matter content of soils and from the above it can be seen that one of the prime objectives of tillage, especially in the arid and semi-arid farming areas, should be to maintain suitably high levels of organic matter in the soil. However, over most of the world, intensive tillage systems have been the most common tillage systems in use, and these have led to substantial decreases in the retention of crop residues and in the levels of organic matter in arable land. This in turn has led to increased wind and water erosion, land degradation and reduced crop productivity. Intensive tillage on newly opened land
may produce a flush of nutrients and an associated yield increase, however the benefits are likely to be short term and to decrease with each tillage season.

2.1.3.1. The Composition and Formation of Soil Organic Matter

Soil organic matter consists of a mixture of organic and inorganic compounds of no specific composition. The organic fraction contains compounds of carbon, hydrogen, oxygen, nitrogen, phosphorus, sulphur, traces of other elements and a variety of sugars and acids. An important parameter of crop residues and soil organic matter is the carbon to nitrogen ratio. For soil organic matter this normally ranges from 10:1 to 12:1. Soil organic matter is derived from partially decomposed crop residues, any added animal or green manures, and the microbial cells involved in the decomposition of these materials, the root systems of the previous crops as well as substances exuded from the roots of growing plants.

The formation of soil organic matter is shown diagrammatically in Figure ___ (@ Godwin 1990, p 50, fig. 2.26). One pathway of the decomposing crop residues and manures leads directly to organic matter. The other main pathway is via the microbial biomass. Here the decomposing crop residues and manures provide carbon for the soil microbes to use as a source of energy and cell building material to increase their population size and hence mass. Some of the by-products of this activity are nutrients that are then taken up by plants. Other by-products of this microbial activity as well as the mass of microbes themselves, together with the decomposing matter they are living off, make up additional soil organic matter. The loss of soil organic matter by decomposition by microbes is also continually underway. The relative rates of formation and destruction of soil organic matter by decomposition determines whether it increases or decreases. Tillage affects the rate of decomposition by increasing the air and oxygen supply to the microbes, which increases microbial activity and hence increases the rate of decomposition. Even when crop residues are incorporated into the soil, tillage generally acts to increase the rate of decomposition of soil organic matter faster than it increases the rate of decomposition of the crop residues. Hence, tillage operations generally reduce the total organic matter content of soils. This is discussed further in the next section.

2.1.3.2. The Properties of Soil Organic Matter

Soil organic matter affects many soil properties, the most important of which are listed in Table ___ (@ Godwin 1990, p 41, table 2.6). A very important property of soil organic matter is that it can combine with clay particles to form soil aggregates. This occurs through hydrogen bonding, electrostatic attraction, and by the physical cementing of soil particles together with polysaccharides and gums. The microorganisms themselves can aggregate soil particles by electrostatic attraction between cell surface and soil particles. The stickiness of microbial cells also tends to aggregate soil particles. Fungal filaments can mechanically bind soil particles together. Microbial cells produce gums as metabolic by-products of residue decomposition that also promotes soil aggregation. If the residues are low in nitrogen, and if supplemental nitrogen is not supplied during the decomposition process, massive quantities of extra-cellular polysaccharides and gums are produced which can physically glue particles together. However, as will be discussed later, low levels of nitrogen in the residues can result in the nitrogen in the soil being bound up and not available for plant uptake.

Soil organic matter plays a crucial role in the formation of soil aggregates, and especially of water stable aggregates, as its solubility in water is limited. As shown previously, good aggregation, and especially the preponderance of water stable aggregates, has many beneficial attributes for crop production. Furthermore, organic matter has a water holding capacity much larger than any other soil component and this, in addition to its beneficial effect on soil structure, markedly increases the water holding capacity of soils, especially of sandy soils. These attributes lead to improved soil aeration, water infiltration and water retention.
They also lead to improved root penetration and resistance to compaction, and increased resistance to wind and water erosion.

As Godwin (1990) points out another very important property of soil organic matter is its role in the release of plant nutrients. The major portion of potential plant nutrients in organic materials and soil organic matter are normally held as part of the chemical structure of larger organic molecules. These cannot be taken up by plants, and are released in mineral or available form, such as nitrogen, phosphorus and sulphur, during microbial decomposition of soil organic matter, crop residues, and dead microbial tissue. The overall process is called mineralisation. Generally the rate of nutrient release through mineralisation depends on climate, vegetation, soil type, intensity of tillage, and residue management.

Nitrogen cycling from the addition of organic wastes and residues to soils, as well as from artificial fertilizers, is illustrated in Diagram ____(@ Godwin 1990, p 49, fig. 2.25). Artificial fertilizers are generally composed of minerals and can be taken up by plants without needing to be processed by the soil microorganisms. However, as crops decompose, a supplemental nitrogen based fertilizer may be required to maintain an optimum rate of residue decomposition if the Carbon:Nitrogen ratio of the residues is greater than about 25:1. (From the previous section it will be remembered that the C:N ratio of soil organic matter is roughly 12:1 to 10:1). If nitrogen is limiting and there is an available supply of carbon, the microorganisms will readily utilise mineral nitrogen from the soil or fertilizers for growth and metabolism. The conversion of inorganic nutrient forms, such as nitrate or ammonium nitrogen, into organic configurations within the microbes is called immobilisation. Although such occurrence is short-lived, and usually followed by mineralisation, it can rapidly lead to severe mineral deficiencies in higher plants. If residues with a high C:N ratio are incorporated into soil that is unable to supply adequate nitrogen for the residue to decompose and a crop is seeded during this period, the crop will be nitrogen-deficient until nitrogen mineralisation occurs. Legumes have lower C:N ratios than non-legumes. Furthermore, the legumes provide more nitrogen for subsequent crops than non-legumes, both by the release of nitrogen from the decay of above ground residues, as well as by the nitrogen fixed on the roots by soil bacteria.

Organic matter can greatly increase the availability of certain micronutrients to plants by the formation of chemical compounds and stable complexes. It can also increase the cation exchange capacity of soils (CEC), which is the maximum quantity of total cations, of any class, that a soil is capable of holding, at a given pH value, available for exchange with the soil solution. It also imparts a buffering capacity to soils that helps to resist drastic changes in pH. In excessively alkaline soils, i.e. those with a pH generally above 7.5, crop growth is frequently reduced because of adverse effects of salinity on both plants and soils. In excessively acidic soils, i.e. those with a pH generally below 6.0, the availability of some plant nutrients, such as calcium and magnesium, is decreased and the activity of phytotoxic ions, such as aluminium, may increased. Thus extremes of soil pH can adversely affect crop growth. This also decreases the amount of plant biomass for potential incorporation into soil organic matter.

Generally, for cultivated soils, the larger the microbial biomass and organic content of the soil the larger the pool of available plant nutrients, and this decreases the need for mineral fertilisers. However in most cases the microbial biomass and organic matter content of a soil cannot be practically increases over that found under virgin conditions, except when irrigation is used or when large amounts of organic wastes are applied.

2.1.3.3. Factors Affecting the Dynamics of Soil Organic Matter

Soils containing 12-18% soil organic matter are generally classified as organic soils with the organic matter content of soils ranges from 90% in low-lying wet areas, to values of 1% or less in semi-arid regions. In some semi-arid regions the organic matter content may be as high as 3%, but generally these high levels are associated with fine-textured soils and cool
climates. The equilibrium level of soil organic matter is determined by the relative rates of soil organic matter formation and breakdown, as already outlined. The rates of organic matter formation and breakdown are in turn dependent on a number of interacting factors including precipitation, temperature, soil textural class, and the tillage and cropping systems. With regard to the latter, the most important aspects are the intensity of tillage, the kind and amount of residues and other organic wastes applied to the soil, the method of application, and cropping practices such as rotations, multiple cropping, etc. Tillage generally facilitates the loss of soil organic matter, by increasing porosity which increases the oxygen supply to the soil microbes, which increases their activity and hence the rate at which they decompose the soil organic matter.

The mean residence time of organic matter is defined as the length of time after formation that one-half of a specific amount of soil organic matter would decompose. The length of time that soil organic matter, or humus, lasts in the soil can also be expressed in terms of the percentage mineralisation per year. In West Africa in the savannah, with an average annual precipitation of 250 to 800 mm, humus mineralisation during the cropping season is in the order of 4 to 5% per year. By contrast, the north temperate semi-arid regions have a humus mineralisation rate of about 2% per year.

As previously outlined, the decomposition process both creates organic matter from crop residues in the first instance, and is also responsible for the breakdown of soil organic matter. Hence, the factors that facilitate decomposition affect both the formation and breakdown of soil organic matter. Furthermore, when the decomposition rate increases this is due both to increased activity of soil microorganisms as well as an increase in their population size and hence mass. As the mass of microorganisms is also a constituent part of the soil organic matter, an increase in the rate of decomposition of soil organic matter, and hence its breakdown, is partly balanced by the increase in the mass of microorganisms. It should also be noted that the crop residues and the organic matter are frequently in different micro-environments, and hence the relative rates of decomposition may be different. However, the overriding factor is that the soil organic matter is already highly fragmented and hence its rate of decomposition is much faster than the largely intact segments of crop residues under the same micro-environmental conditions. This means that tillage operations, or factors that increase the rate of decomposition, increase the rate of loss of soil organic matter. The main factors affecting the dynamics of soil organic matter are discussed below.

A. Water

The decomposition of organic wastes and residues in soil is mainly dependent on soil microorganisms that require water for their growth and activity. However, if too wet, water can limit oxygen diffusion and the system will become anaerobic, thus slowing the rate of decomposition. Decomposition is generally rapid at a water potential of about -0.3 kPa and generally decreases below this value. Bacterial activity decreases below water potentials of -0.3 kPa and falls off rapidly below values of -0.5 MPa. Although fungi can grow at much lower water potentials than bacteria, e.g. -5.0 MPa, the decomposition of organic residues at low water potentials is much slower than under wetter conditions.

Water also determines to a large extent the amount of higher plant biomass that can be grown in a particular area. This in turn determines the potential amount of crop residues including old root growth that can be retained in the field to be decomposed into soil organic matter.

B. Temperature

Temperature is another important factor that controls soil organic matter dynamics. Generally, within limits, chemical reaction rates are doubled for each 10 deg. C rise, provided that the necessary reactants are available. From various studies that have been done it is likely
that the turnover rate of soil organic matter follows this relationship, provided that lack of adequate water is not a limiting factor. The interacting relationships between temperature and water are very important in determining the effects of different tillage systems.

Soil microorganisms can function over a wide temperature range, from roughly 0 to 60 deg. C, but exhibit maximum activity in the range 20 to 30 deg. C. However even at optimum temperatures, decomposition will be slow if water is limiting.

C. Soil Acidity/Alkalinity (pH)

The optimum pH range for rapid decomposition of crop residues and organic wastes is 6.5 to 8.5. Deviations from this range can slow the decomposition rate of crop residues and of organic matter, as well as lead to a reduction of the microbial biomass. As previously pointed out, deviations from this range can also lead to a reduction in the higher plant biomass which in turn leads to a reduction in the potential return of crop residues.

D. Carbon: Nitrogen Ratio

The chemical composition of crop residues and organic wastes determines the rate and extent of their decomposition by soil microorganisms, as well as the resulting content of the soil organic matter. The soil microorganisms use the carbon and nitrogen for metabolism and growth. Most crop residues contain about 40% carbon and as the C:N ratio increases, i.e. as the proportion of nitrogen decreases, so the rate of decomposition decreases. As discussed in Section 2.1.3.2 if organic wastes or crop residues that contain large amounts of readily oxidisable carbon but low levels of nitrogen are applied to the soil, then a high microbiological demand for nitrogen can be induced. If this demand is not met by the nitrogen within the residue, then mineral nitrogen from the soil and from fertilizers will be used. While this is being used it is immobilised within the microorganisms and is not available to higher plants. If the demand is such that all the available mineral nitrogen is required by the microorganisms then this can lead to severe mineral deficiencies in higher plants.

Usually organic residues with C:N ratios of 25:1 or less, or a nitrogen content of about 1.5%, will not be nitrogen deficient during decomposition. However, most cereal straws have C:N ratios that range between 80:1 and 120:1 and these do require supplemental nitrogen. Sulphur and phosphorous can also be limiting during the decomposition process. Legumes have lower C:N ratios than non-legumes and are never nitrogen deficient during decomposition. Although the C:N ratio is useful in predicting decomposition rates and additional nitrogen requirements, the carbon or nitrogen contents of different plant residues may differ in their availability to microorganisms. For example, in plants in which the carbon content is composed largely of lignin, or where the nitrogenous components are highly resistant to decomposition, then the C:N ratio needs to be used with caution.

E. Termites and Earthworms

While microorganisms are the prime agents of decomposition, other organisms such as termites and earthworms may also play a significant role where they occur. Both feed on detritus and crop residues and also move these from the surface to deeper layers. Furthermore their burrows have a beneficial effect on soil aeration and water infiltration. Intensive tillage is likely to discourage both from colonising agricultural lands. However in some circumstances, and above certain population levels, termites are an agricultural pest.

F. Crop Residue Return

The means used to return crop residues to the land affect the decomposition rate primarily through the factors already discussed. If the residues are left on the surface they are subject to rapid drying, and greater fluctuations in temperature and moisture than if they are
buried or incorporated into the soil. This results in a slower rate of decomposition for residues left on the surface. However, as previously discussed, this results in higher soil organic matter levels due to the effect of other factors.

The return of crop residues or other organic matter to the soil will generally increase both the organic matter and the nitrogen contents of the soil. Table ____ (@ Godwin 1990, p 48, fig. 2.9) shows the results of a 27 year study of the change in organic matter content and nitrogen levels of a fine sandy loam soil with different rates of return of crop residues. With no residue return there was a net loss of 2685 kg/ha of organic matter that resulted in a decline in organic matter content from an initial 1.5% in 1922 to 1.3% in 1940. Only the maximum rate of residue return resulted in no net change in soil nitrogen. From the data it can be seen that in order maintain the soil organic matter at an equilibrium rate, for these soils and under the tillage systems used and the prevailing climatic conditions, that the straw return rate needed to be roughly 1400 kg/ha. In order to gradually increase the level of organic matter a higher application rate would be needed.

2.1.3.4. The Effect of Tillage on Soil Organic Matter and Nutrients

The tillage systems used in arable land have a major effect on the levels of soil organic matter and nutrients derived from crop residues. Various tillage systems can be used to either leave crop residues on the soil surface, to mix them in the shallow soil layers, to completely bury them below the soil surface, or not to incorporate them at all.

With most conventional tillage systems only limited amounts of crop residues are left in the field and these are completely buried. The soil is also tilled intensively in order to control weeds and to prepare a fine tilth for the seedbed. This process hastens the decomposition of organic carbon and nitrogen compounds. This can be seen from studies carried out on virgin soils in the USA over a period of 60 years, illustrated in Figure___ (@ Godwin 1990, p 52, fig. 2.27). The conventional tillage practice used was mouldboard ploughing to 150 mm depth, followed by discing and other tillage operations. No crop residues were retained. Fifty percent of the soil organic matter and about the same amount of organic N was lost during the first 20 years of cultivation. The loss was most rapid during the early years of cultivation, but after 50 years some equilibrium was reached. The equilibrium point and the time required to reach it will depend on climate, soil type, rate of residue return and level of erosion. As discussed in Section 2.1.3.3.F., if the rate of residue return is adequate, then there need not be a loss of soil organic matter and nitrogen. However, as the tillage intensity increases so too does the amount of crop residue required to be returned, in order to keep the soil organic matter and nitrogen levels constant. In arid and semi-arid regions, where the total amount of vegetative production may be low, there may be inadequate amounts of crop residues to retain this balance even if all the residues are returned.

Besides speeding up microbial decomposition, intensive tillage also breaks down the soil aggregates, making the soil particles, soil organic matter and nitrogen compounds more susceptible to erosion. Furthermore, erosion is a selective process, and soil organic matter and nitrogen compounds erode at a higher rate than soil particles. The organic matter and nitrogen content of soil sediments removed by erosion is often more than twice that found in the soil from which the erosion occurred. Considering that fertilizers are one of the major input costs for small and medium-scale farmers this attribute of erosion is very important. Even if fertilizers are not used by the poorer farmers, the effective cost of the loss of nutrients through erosion can be expressed to them, by extension workers, in terms of equivalent fertilizer cost and reduced yield.

Figure ____ (@ Elwell 1992, p 27, table 3) shows the effect of different tillage operations on organic carbon and water stable aggregate levels on both clay and sandy soils. Organic carbon levels and the number of water stable aggregates were found to be lowest under
conventional annual ploughing irrespective of whether residues were returned or not. Using only ripping operations led to substantial improvements in organic carbon and water stable aggregate levels. An important finding was that ploughing in maize residues did not significantly improve soil structure compared to ploughing with no residue returned. This appears to contradict much of the work carried out in the USA where residue return under conventional ploughing made significant differences to the levels of organic matter present, see Figure ___(@ Godwin 1990, p 48, table 2.9). However, these differences are still minimal compared to the improvement in these parameters under reduced tillage systems.

Generally, tillage operations cause a decrease in the size of the microbial biomass. The decline in microbial biomass results in a loss in nutrient cycling capability as well as the possibility of soil structure deterioration, leading to decreased water infiltration and increased soil crusting.

Under reduced tillage systems and especially zero-till, with the crop residues retained on the surface or partially mixed into the soil surface, the soil is mixed less, or not at all. This slows decomposition and conserves organic carbon and nitrogen near the surface as both organic matter and microbial biomass. After a time, soil organic matter and the microbial biomass will generally increase, especially near the surface, and this will lead to an improved nutrient cycling ability. Surface residues will protect the soil against wind and water erosion and improve moisture conservation. This will lead to an improved soil structure, improved water infiltration and soil aeration, and reduce crusting.

A simple test to determine whether a soil has good structure and whether the levels of soil organic matter are good is given by Elwell (1989). This test can easily be used by farmers and extension workers to measure the effect on the soil of the tillage systems that are being used and the effectiveness of improved systems. For clay soils the test is based on the stability of clods when immersed in water, a property imparted by the presence of soil organic matter. For sandy soils the test is based on a visual indication of the presence of organic matter. The test for structure and soil organic matter is given below:

Clay Soils:
- Dig up some large clods from the arable block and break them down to give 10 to 20 small clods about 1 cm in diameter.
- Prepare the same number of clods from virgin land of the same soil type at the edge of the field.
- Drop the sets of small clods into separate glass jars of water and observe what happens.
  - When the soil is in good condition the clods will not disintegrate in water but will remain intact under water for months. In the field these soils will remain open and porous throughout the rainfall season and have good infiltration and good water holding capacity properties.
  - When the soil is in poor condition the clods will collapse quite quickly. In the field these soils will show marked signs of collapsing into a dense mass with the onset of rains, leading to a low infiltration, high runoff, and erosion losses of soil and nutrients. The soil will also be difficult to plough, giving rise to very large hard clods and will require several secondary tillage operations to form a fine tilth.

Sandy Soils:
- Dig up a soil sample from the arable block and one from virgin land of the same soil type at the edge of the field.
- Moisten them and compare the difference in colour. Generally, the greyer the colour of the soil the higher the organic matter content and the better its condition.

The fertility of these soils depends to a very large extent on the amount of organic
matter present, not in terms of producing water stable clods, but by improving structure through spacing out the soil particles, and by the properties of soil organic matter itself. Sandy soils in good condition will lead to high infiltration, low runoff, low erosion losses of soil and nutrients, and will be able to hold more nutrients and transfer them more efficiently to the plants.

2.1.3.5. The Control of Organic Matter and Plant Nutrient Levels in Soils

From the previous sections it can be seen that the soil organic matter content and fertility of soils can be increased through several ways. These include the following:

- Regular addition of organic carbon and nitrogen to soil:
  - Retention of crop residues on the land.
  - Addition of organic wastes.
  - Use of green manures.

- Addition of nitrogen:
  - Inclusion of legumes in the rotation.
  - Use of mineral fertilizers.

- Reduce tillage operations, to reduce decomposition of soil organic matter:
  - Use of zero-till systems with the retention of crop residues to protect soil surface, reduce water runoff and increase infiltration.
  - Use of reduced tillage operations with partial incorporation of crop residues to protect soil surface.

- Improve water balance:
  - Reduce runoff and improve infiltration, through retention of crop residues on surface, and/or appropriate tillage systems, e.g. tied-ridging, pot-holing, chisel ploughing to increase infiltration, etc.
  - Reduce soil water evaporation, through retention of crop residues on surface, or shallow tillage to break capillary action.
  - Use of supplementary irrigation.
  - Use of fallow periods.

- Reduce soil temperature in high temperature regions:
  - Retention of crop residues on surface.

- Establish acceptable pH levels:
  - Use of minerals and manures to attain correct pH levels.

In many arid and semi-arid regions there are competing demands for crop residues. The most important of these are their use as fodder, and in many regions crop residues form the main source of feed for livestock during dry winter months. Because of the importance of the retention of crop residues on the land it is very important that adequate amounts of residues are returned to arable fields. The minimum amounts of surface residue retention required to adequately protect and return organic matter to the soil needs to be identified for each region. Strategies need to be developed to reduce the use of crop residues as fodder, and this requires a more rational use of natural grazing, e.g. rotational grazing, controlling livestock units per hectare, growing of fodder crops, etc., all of which require major extension programmes. Crop residues are also used as fuel and fibre and in these cases strategies need to be developed to develop alternative sources, e.g. fast growing tree species for woodlots.

For soils that have been severely eroded, and are of low subsoil fertility, special management practices in addition to the above may be required. One of these management practices is deep soil-loosening with the deep placement of phosphorous, together with the retention of crop residues and the use of a legume in the rotation. The objective of the deep placement of the phosphorous is to encourage deep rooting of the plants into the subsoil. This achieves both an increase in the depth of soil from which the plants can draw water, as well as a later increase in the organic matter content of the soil due to the increased plant root mass available for decay, and its dispersion through a greater volume of soil.
2.2. **SOIL EROSION**

The degradation of land through various processes, the most common of which is soil erosion, leads to reduced current and future productivity of the land, both in terms of quantity and quality. Rauschkolb (1971) proposed three categories of land degradation, based on decreasing importance in terms of aerial coverage, intensity of rate of degradation, and impact on soil productivity, and these are listed below:

Category 1.
- Soil erosion due to wind and water, including:
  - Silt deposition.
  - Desertification and dune creep.
- Salinization and alkalization.
- Organic wastes.
- Infectious organisms (weeds, diseases, insects).

Category 2.
- Industrial organic wastes.
- Pesticides.
- Radio-active substances and heavy metals.

Category 3.
- Fertilizers.
- Detergents.

The types of land degradation included in Categories 2 and 3 were classified as of lower importance than those in Category 1 primarily because of their lesser extent, intensity, or rate of increase.

All types of land degradation outlined above can be significantly influenced by the type of tillage and management systems used. Because of the importance of land degradation, it is a crucial consideration in the selection of tillage and management systems, both in terms of restoring land following degradation, and of avoiding degradation in the first instance. In this report only soil erosion due to water and wind will be considered in detail. The management of organic wastes and infectious organisms are an integral part of tillage and management systems and their relevance to tillage will be covered in appropriate sections. Silt deposition is a consequence of soil erosion and to a large extent this also applies to desertification and dune creep. These together with salinization and alkalization are briefly covered by Unger (1984) and a series of references for further study are also given in that report.

Soil erosion and its associated sedimentation, as a natural geological process occurring over millions of years, has been responsible for the creation of the main agricultural areas farmed today. However, accelerated soil erosion on arable and grazed land associated with human activity is the major form of the degradation of agricultural land today. The several centimetres that can be lost in one or a few wind or rainstorms has generally taken hundred or thousands of years to be formed. Soil erosion is now reducing agricultural output in many countries by both reducing yields on farmed land and rendering vast areas of land useless from the point of view of agricultural production. This in turn leads to numerous economic and social problems, depending on the intensity and extent of land degradation. As Constantinesco (1976) points out, producers may suffer economically from destroyed crops, lower yields, and the necessity for increased inputs such as additional fertilizers, tillage for erosion control, tillage or other means of correcting damage due to erosion, and the application of other erosion control measures. These in turn lead to less money being available for other goods and services. As erosion becomes more intense and affects larger areas, food shortages may
develop and lead to civil strife, settlements may be abandoned and people may be forced to migrate to other regions or countries.

The main forms of soil erosion are by wind and water. In most parts of southern Africa the main form of erosion is due to water, whereas in some countries wind and water erosion are both of major importance, for example in the USA. Tillage erosion due to the incorrect implementation of primary tillage operations is also a widespread problem in the small-scale farming areas.

2.2.1. Water Erosion

Soil erosion due to the action of water on unprotected lands generally increases with the intensity of the rainfall and the steepness of slope of the lands. Lands highly susceptible to water erosion include those in much of Africa, South and Central America, southern North America, southern Europe, southeast Asia, Australia, New Zealand, the Caribbean islands, and most Pacific islands (Constantinesco 1976). On lands where erosion is not adequately controlled the problems are severe.

Soil erosion due to the action of water has been classified into three categories, namely:

- Sheet erosion:
  This is the uniform loss of soil from land. Results of sheet erosion are often manifest by light-coloured patches of soil or exposed rocks.

- Rill erosion:
  When the soil loss is still fairly uniform but concentrated into numerous minute streams, or rills, it is termed rill erosion.

- Gulley erosion:
  When the flow is concentrated at low points on the lands and this flow starts to form gullies, then it is termed gulley erosion.

Although gulley erosion is the most obvious of the three, most soil loss on crop lands is due to sheet and rill erosion (Hayes and Kimberlin 1978). Most of the discussion in this section will concentrate on these two forms.

Extremely high levels of water erosion have been recorded, some over 1000 tonnes/ha/yr. More typical average values of water erosion on unprotected lands are those estimated in Zimbabwe for the small-scale farming areas of 50 t/ha/yr. The sandy soils there are generally shallow, and with a soil formation rate of less than 1.0 t/ha/yr, Elwell (1983) has estimated that lands under cultivation in Zimbabwe only have a lifespan of 30 to 50 years after they have been opened up for cultivation. In the USA the so-called tolerable level of erosion is 11.2 tonnes/ha/yr (5 tons/acre), which is equivalent to a uniform removal of 0.8 mm of topsoil, assuming a bulk density of 1.4 t/m$^3$.

Besides the serious impact of the loss of topsoil on the lifespan of a soil, the erosion process also leads to a disproportionately high loss of soil nutrients and organic matter. Elwell and Stocking (1988) showed that twice the amount of nutrients are eroded from the soil than would be expected, judging from the total weight of soil eroded. On a national basis this leads to an astronomic financial loss, either in terms of fertilizer applied to compensate for the nutrient loss, or in terms of lost yield if additional fertilizer is not applied. To the farmer this means that roughly up to half the fertilizer and organic matter applied to the field can be washed away. In addition, the erosion process requires water runoff and in arid and semi-arid areas this loss of water severely limits yield. In the above study up to a third of the seasonal rainfall was estimated to be lost as direct surface runoff. Erosion can also directly reduce yields by the removal of seed, seedlings and young plants, or incur the costs of corrective tillage and reseeding.
Furthermore, the sediments resulting from the erosion by water in the catchment areas of dams is reducing the life of many on-farms dams to less than 5 years and major dams to 10 to 20 years in Zimbabwe. This results in large losses of capital expenditure and also frequently of infrastructure supporting agriculture, e.g. dams for irrigation schemes.

2.2.1.1. Factors Influencing Water Erosion

There are two main processes involved in soil erosion by water. The first involves the detachment of soil particles from soil aggregates and the second, the transport of these particles together with other loose particles away from their original position. Both these processes require energy. The detachment of particles from the soil can be caused by both the dissipation of the kinetic energy of the impacting raindrop on the soil, as well as by the kinetic energy in water flowing over the soil. The transport of soil particles is by water runoff. Although soil particles can be transported short distances by raindrop splash action, this is inconsequential in comparison to transport by water runoff. Soil that has a sizable proportion of detached soil particles on the surface is more prone to erosion, because no energy is required to detach them and they can be transported from their original position as soon as runoff occurs.

There are several factors pertaining to rainfall that determine its erosive potential, and these are described below:

- Kinetic energy of the raindrop:
  The kinetic energy of a raindrop is equal to half its mass times the square of its velocity. The velocity of a falling raindrop increases with its mass, and hence an increase in mass has a large effect on increasing a raindrop's kinetic energy. The higher the kinetic energy of the raindrop at the time of its impact on the soil, the greater is its capacity to detach soil particles.

- Intensity or rate of rainfall:
  The rate of rainfall, in terms of mm rain per unit time, is important because if it exceeds the maximum infiltration rate of water into the soil, and if it is not held on the surface where it falls, then runoff occurs. Furthermore the higher the runoff rate the higher the potential for erosion.

- Duration of rainfall:
  The duration of rainfall is important because the maximum rate of water infiltration into soil decreases markedly with time, as discussed in Section 2.1.2.3. Hence, even if the soil can initially absorb all the water falling on it, this situation may change after time, allowing runoff to occur.

  The size of raindrops formed during convection rainstorms, i.e. thunderstorms, are large, and their intensity in terms of mm rain per hour is also high. As these rainstorms are common in the tropics and subtropics, the erosive potential of rainfall in these areas is much higher than in the temperate regions. However, the duration of individual rainfall events in the tropics is generally lower than in the temperate regions, and to some extent this mitigates the effects of higher raindrop energy and rainfall intensity. When a rainstorm starts while the soil is still wet, as is common in areas of high rainfall, the initial water infiltration rates may already be low and this may lead to high rates of runoff, and hence increase erosive potential.

  The major portion of the annual loss of soil from a field due to erosion is frequently due to only a few high intensity storms. This may be due solely to the intensity and duration of the storm, or one storm quickly following another while the soil is still wet and has a low infiltration rate, or if the storm occurs early in the season while there is little crop cover.

  On bare soil the impact of raindrops on the soil surface detaches soil particles from aggregates and any runoff will then transport these particles, and existing loose soil particles, to another location. As the impact of raindrops partially breaks up soil aggregates, and
especially aggregates which are not water stable, this also leads to surface sealing or crusting as the loose soil particles fill the surface pores, as well as to reduced surface roughness. This in turn leads to decreased water infiltration and increased runoff, and so increased transport of soil particles from their original position, and hence increased soil erosion.

In addition to the characteristics of the rainfall itself, the other factors that influence the rate of soil erosion are those that influence the detachment of soil particles, the infiltration rate and the amount and speed of runoff. These are listed below:

- Factors affecting the detachment of soil particles from surface aggregates:
  - Falling raindrops can be intercepted by two means:
    - Leaves of crops. The amount of cover and the time that the cover is present in relation to seasonal variations in the intensity of rainfall are both important factors.
    - Crop residues. The amount of cover on the soil surface is an important factor.
  - Binding strength of soil particles to aggregates, which are influenced by the soil organic matter content.

- Factors affecting infiltration rate:
  These factors have been discussed in previous sections and include the following:
  - Presence/absence of adequate amounts of crop residues on the soil surface. Adequate amounts of crop residues protect soil aggregates from breaking up and the particles from filling up pore spaces and so reducing infiltration.
  - Levels of organic matter content. As levels increase so does aggregation and hence pore space and hence infiltration rate. As levels increase so does the proportion of water stable aggregates increase.
  - Soil texture. The coarser the texture the higher the water conductivity and the higher the infiltration rate.
  - Degree of soil aggregation. The higher the aggregation the higher the water conductivity.
  - Proportion of water stable aggregates. The higher the proportion of water stable aggregates the less the soil will slump when wet and so hydraulic conductivity will remain high. Also, the higher the proportion of water stable aggregates the less the surface aggregates will disintegrate under raindrop impact, and this will also assist in retaining high infiltration rates.
  - Bulk density. The lower the soil bulk density the higher the porosity and the higher the water conductivity.
  - Degree of fracturing. The higher the degree of soil fracturing the higher the water conductivity.

- Factors affecting the quantity of runoff:
  - The quantity of runoff is determined by the difference between the rate of precipitation and the rate of infiltration, and several other factors including the following:
    - The amount of water that can be held where it falls on the soil surface until it infiltrates. The more water that can be held the less the runoff.
    - Length of field slope. The quantity of water flowing over a particular point is the accumulated runoff "upstream" of that point. The shorter the length the less the runoff.

- Factors affecting the speed of runoff:
  - Steepness of field slope: If runoff is occurring, then as the steepness of the field slope increases so does the speed of runoff.
  - Roughness. As roughness increases the speed of runoff decreases, because roughness acts as an obstruction and frictional resistance to flow. Because of this it can be expected that the speed of runoff is also partly affected by the quantity of runoff. Within limits, as quantity of runoff increases so does the speed. Roughness can be due both to cloddiness and crop residues on the surface.
The factors influencing erosion have been extensively studied and reviews and guidelines pertaining to erosion control have been published by numerous authors, including Elwell (1983), FAO (1978), Hayes and Kimberlin (1978), Kimberlin (1976), Stewart et al (1975), Wischmeir (1973), and Wischmeier and Smith (1978).

2.2.1.2. Estimation of Soil Loss due to Water Erosion

The ability to estimate the annual loss of soil from a particular field, for a range of different cropping and tillage practices, is an important tool in extension, planning and design work. The most immediate advantage of being able to estimate soil loss is that the conservation objective of reducing soil losses to specified acceptable levels can be formulated. Once this level has been established, for a particular soil in a particular region, then cropping, tillage and conservation practices can be drawn up for a particular field so that the mean soil loss can be maintained below this level.

Soil loss estimation can be used by extension workers to explain to farmers the quantity of soil they are currently loosing, why it is being eroded and how the loss can be prevented. An integrated cropping and conservation system can be drawn up appropriate to a particular farmer’s circumstances and sold as a production/protection package deal. The influence of new crops or cultivation practices on soil erosion can be evaluated before they are widely adopted. Reliable soil loss estimates also play an important role in land use planning, particularly in helping to determine whether a certain soil life can be tolerated.

Another advantage of the use of soil loss estimation systems is that in learning to use the system extension staff obtain a very good grounding in the basic factors contributing to erosion and how these interact with each other. However, if a soil loss estimation model is not yet in use in a specific country this should not be used as a reason for not implementing a comprehensive erosion control programme. The establishment of the model could become part of the programme and until then the standard control measures should be implemented.

The most common soil loss estimation model in use is the Universal Soil Loss Equation (USLE), developed in the United States. The model is described in detail by Stewart et al (1975), and values for the factors of the equation are given for many locations in the USA. The model is given below:

\[ A = R \times K \times L \times S \times C \times P \]

Where:
- \( A \) - Predicted mean annual soil loss. (Units: tons/acre/yr).
- \( R \) - Erosive potential of rainfall, designated El 30, of a normal year’s rainfall at a specific location.
- \( K \) - Soil erodibility factor, or the mean soil loss per unit of \( R \). (Units: tons/acre/unit of \( R \)).
- \( L \) - Length of slope factor.
- \( S \) - Slope gradient factor.
- \( C \) - Crop Management factor.
- \( P \) - Erosion control practice factor.

The factors other than \( A \) and \( K \) are unit less. \( A \) and \( K \) can also be expressed in terms of tons/acre.

An alternative soil loss estimation model is in common use in Southern Africa, known as the Soil Loss Estimation System For Southern Africa (SLEMSA). The model is described in detail by Elwell (1977), and the design of safe rotational systems using this model is described by Elwell (1980). This system was developed because of disadvantages identified in the American method for use in southern Africa, viz: its dependence upon expensive and long term
field-plot measurements, difficulties in drawing parallels between American and southern African environments and uncertainties in translocating data from one continent to another, (Elwell 1977). From validation exercises carried out in Zimbabwe the SLEMSA model was found to be more accurate in estimating soil loss there than the USLE model. The SLEMSA model combines three sub-models and is given below:

\[ Z = K \cdot C \cdot X \]

Where:

- \( Z \) - Predicted mean annual soil loss. (Units: tonnes/ha/yr)
- \( K \) - Mean annual soil loss from a standard field plot of 30 m x 10 m at a slope of 4.5\% for a soil of known erodibility, \( F \), under a weed free bare fallow, and for a known rainfall energy, \( E \). (Units: tonnes/ha/yr).
- \( C \) - Ratio of soil lost from a cropped plot to that lost from bare fallow.
- \( X \) - Ratio of soil lost from a plot of length \( L \) and slope \( S \), to that lost from the standard plot.

In the sub-models, \( K \) is a function of rainfall energy \( (E) \), and also a function of the soil erodibility \( (F) \). \( E \) is based on the mean annual rainfall of the particular location and together with \( F \) is used to translate the data collected from the series of replicated plots at one research station to any other location. This methodology is much cheaper to research and to establish the basic data for than the American system, as in the American system data had to be collected over a long period of time and from a number of different replicated plots spread over the country.

As previously outlined, the use of a soil loss estimation model is important from a conservation and extension point of view. In addition to the two models described above there are also other models. Which system to use will depend mainly on which models are currently in use, but the appropriateness of competing models to a particular country should be tested.

2.2.1.3. Control of Water Erosion

The control of water erosion is one of the main criteria in the selection of appropriate tillage, cultivation and management systems. Because of the direct causal association between water runoff and erosion it also needs to be emphasised that the tillage systems selected to control water erosion are frequently also those selected to conserve water. As discussed in Section 2.1.2.3 water falling onto the soil surface either infiltrates into the soil surface, or is retained on the surface, or flows down the slope as runoff. The main means of control of water erosion are directly related to the factors influencing erosion discussed previously. These are listed below and then discussed in the order given:

- Reduce detachment of soil particles from surface aggregates:
  - Use soil cover to protect soil from raindrop impact:
    - Increase crop cover during periods of high erosive potential through selection of crop type, or appropriate cultivation or management systems.
    - Retain crop residues on surface through selection of appropriate tillage systems.
  - Increase binding strength of soil particles to aggregates by increasing soil organic matter content.
- Increase infiltration rate:
  - Increase amounts of crop residues on surface.
  - Increase degree of soil aggregation.
  - Reduce bulk density.
  - Increase degree of fracturing.
- Increase length of time that infiltration rate remains high:
Increase proportion of water-stable aggregates.
Increase depth of tillage and ensure no impermeable layers.

- Increase length of time that water can be held where it falls on the soil surface to increase length of time for infiltration to take place:
  - Increase surface roughness through increasing cloddiness or retention of crop residues on the surface.
  - Implement all tillage and planting operations on-contour or slightly off-contour.
  - Use tied-riding or pot-holing tillage operations.

- Reduce the speed of runoff:
  - Use tillage operations such as ridging slightly off-contour.
  - Use strip cropping systems to provide obstacles to flow.
  - Use mechanical conservation works, e.g. construction of contour ridges, waterways, terracing, etc., to reduce the down slope length of the field or reduce the steepness of slope.

The use of soil cover to absorb the impact of raindrops and so reduce soil particle detachment from soil aggregates is one of the most important methods of erosion control. The reduction of soil particle detachment not only results in soil particles being less available for transport by runoff, but also means that fewer soil particles are available to block up soil pores and hence reduce infiltration rate, and hence increase runoff and erosion. Soil cover can be provided both by growing plants and by crop residues. Of key importance is the provision of cover during the whole period in which erosion can occur and particularly during periods of maximum rainfall erosive potential. Papendick and Miller (1977) found that the continuous cropping of high-residue small grains to be one of the most effective soil and water conservation practices, especially when supplemented with residue-based tillage practices and when the crop is growing during the major period of erosion. The small grains used were densely planted and so provided good soil cover and their closely spaced stems impeded runoff, and they also produced large quantities of residue for retention. However, the continuous cropping system is generally costly to implement and not as sustainable for small-scale farmers as rotation and multiple cropping systems. These aspects are discussed in Section 3.2.2. The use of multiple cropping systems, and especially strip cropping, to provide cover is a very important means of soil and water conservation, and this will be discussed towards the end of this section.

As mentioned previously, the major part of the total annual soil loss is frequently due to only a few storms and if these occur when there is little cover exceptionally severe erosion can occur. In many regions the periods of maximum rainfall erosive potential occur at the start of the rainy season and hence occur at the time when plant cover from crops is minimal or non-existent. This is particularly true of those regions in which there are very distinct rainy seasons interspersed with long dry seasons during which crops can not be grown, unless irrigation is used. In these situations the provision of cover from crop residues, or the use of other tillage systems, to provide protection at the start of the growing season is of crucial importance.

The relationship between the amount of cover, from either crops or residues, and its effect on protecting the soil from water erosion is shown in Figure ___ (@ Godwin 1990, p 65, fig. 2.31). As expected the higher the percent soil cover the greater the protection. A commonly used figure for the minimum percentage cover required to give just adequate protection is 30% soil cover. This would result in a soil loss ratio of 0.2, i.e. soil with a 30% cover would lose 20% of that lost from bare soil. At 60% cover the loss would be only 5% of that from bare soil. From this it can be seen that increasing soil cover has a major effect on reducing erosion. Conservation tillage systems are commonly defined as those in which at least 30% of the soil surface are covered with crop residues.

The presence of crop residues on the surface both reduces runoff and also increases the rate of infiltration. It does this by retaining water on the surface, by in effect increasing surface roughness, and by also protecting the surface from raindrop impact and so limiting the
build up of a thin soil layer on the surface with low hydraulic conductivity, i.e. capping or crusting. However, it should also be noted that there are disadvantages to retaining crop residues on the surface, e.g. interference with the operation of machinery, carry over of diseases and pests from the previous crop, etc., and these will be discussed more fully in Section 2.4. and Section 3.

The amount of soil cover given by residues from different crops is highly variable. Table ___ (@ Godwin 1990, p 61, 2.16) lists the percent soil cover given by different weights of residues from different crops. These figures can easily be checked for local crop varieties, or figures calculated for different crops, by using fixed point checks along a traverse line and calculating the percentage of points that fall on crop residues, for different weights of residues. It is important that a statistically representative sample is chosen. In arid and semi-arid regions the total weight of crop residue may be low and furthermore some may be used for alternative uses such as fodder. Hence, before it is decided to use crop residues as the main means of soil erosion control in these regions, it is crucial to determine that adequate amounts are available. If adequate amounts are not available then alternative control measures need to be taken.

Another key erosion control measure is to increase soil aggregation and to increase the proportion of water-stable aggregates. This increases porosity and hence increases the infiltration rate and so reduces runoff. If a high proportion of water-stable aggregates are present then the porosity is maintained once the soil is wet because water-stable aggregates do not collapse when wet. Furthermore, soil particles are less likely to break off from water-stable aggregates under raindrop impact and fill the pores and so reduce infiltration. Increasing the soil organic matter content facilitates soil aggregation and increases the proportion of aggregates that are water-stable. The means of increasing soil organic matter levels in soils was covered in Section 2.1.3.5.

The use of tillage systems to increase the rate of water infiltration, and to hold the water on the surface for sufficient time for it to infiltrate, is of crucial importance in the control of soil erosion. This was covered in detail in the section on water infiltration, namely Section 2.1.2.3. and should be referred to again in the context of the control of water erosion.

As previously discussed, water runoff is reduced by increasing the water infiltration rate, as well as by several other methods which retain the water on the soil surface where it fell, or at least reduce the speed of runoff, in order to allow more time for infiltration to take place. These methods include: increasing surface roughness by selecting tillage operations that leave crop residues or large soil clods on the surface; carrying out all tillage operations on-contour or slightly off-contour so that the surface roughness is orientated to reduce flow down the slope for small and medium sized precipitation events; forming small water retaining structures on the surface, such as ridging slightly off-contour and damming the furrows; pot-holing; and growing closely spaced crops whose stems impede runoff.

The relative effectiveness of various tillage implements in altering soil porosity, cloddiness and roughness is given in Tables ___ (@ Godwin 1990, p 56, fig. 2.11), ___ (@ Godwin p 57 fig. 2.12), ___ (@ Godwin p 57 fig. 2.13). For these various operations to be effective it is important that the soil is at the appropriate moisture contents for the operations. This aspect is covered in Section 5. Tillage implements that cause pulverisation of the soil should not be used on soils prone to erosion. All operations should be carried out either on-contour or only slightly off-contour, so as to provide maximum obstruction to water flow down the slope.

When selecting tillage systems for the control of water erosion it must be remembered that hydraulic conductivity and surface roughness change rapidly during rainfall events. Changes in hydraulic conductivity during a rainfall event are an intrinsic part of soil water movement, as discussed in Section 2.1.2.2, and is the reason why water infiltration changes
with time during a rainfall event. These changes occur during rainfall even if capping does not occur. If capping occurs then, even after drying, the infiltration rate at the start of the next rainfall event is lower than at the start of the preceding rainfall event, unless tillage is performed to break up the surface layer.

The extent that surface roughness changes during rainfall is partially limited by the presence of water-stable aggregates. These changes can be large, as shown in Table ____ (@ Godwin p 66, fig. 2.18). From the table it can be seen that the plough-only treatment resulted in a random roughness of twice that of the plough and disc-harrow treatment, but that after rainfall the roughness of the plough-only treatment was reduced to that of the latter prior to rainfall. The other important feature to note is the total infiltration prior to runoff of the different treatments. From the table it can be seen that total infiltration in the plough-only treatment was three times that of the plough and disc-harrow treatment prior to initial runoff. It can also be deduced from the table that if the plough-only treatment was not tilled prior to the next rainfall event, that the total infiltration prior to runoff during the second rainfall event would be reduced to a third of the amount during the first rainfall event.

From this it can be seen that an important disadvantage of using tillage to control soil erosion without the use of crop residues, especially if the soil organic matter content is low, is that tillage may need to be performed after each rainstorm in order to restore the surface to a non-erodible condition. This requires a high energy expenditure and good timing and management. In addition, each tillage operation facilitates the loss of soil organic matter. However, as discussed previously, although a shallow tillage operation may also result in moisture loss from the tilled layer it will reduce soil water evaporative losses from deeper layers.

The use of tillage to form small water retaining structures on the surface, such as ridging slightly off-contour and damming the furrows, controls erosion by holding water on the surface until it has time to infiltrate. Ridging slightly off-contour without damming the furrows is also commonly used and operates by reducing the speed of runoff. This both gives more time for infiltration and also reduces the speed of runoff and so reduces the erosive potential of the running water. The methodology used in ridge design and construction is given in Section 5. An extremely important aspect to note is that for the use of ridges to be effective, either tied or open, mechanical conservation practices must be implemented and the land on which the ridges are constructed must be even. If this is not the case then the ridges are likely to overflow at a low point, and as the ridges will concentrate the water at the lowest point, this can lead to far worse erosion than if the ridges were not used. If the land is not even, then either ridges should not be used or the land should be levelled prior to ridging. On land that is only marginally uneven and which does not warrant the cost and energy required to level it, then the ridges can be laid out at a gradient steeper than the contour ridges.

The use of various multiple cropping systems, and especially strip cropping, is an important means by which increased cover for the soil from a growing crop can be provided over the rainy season. The general characteristics of these systems are described in Section 3.2.2.3. The inclusion of densely planted small grain crops in the strip cropping system is a very effective means of providing both soil cover as well as providing an obstruction to runoff and so reducing the speed of flow. While the plant leaves protect the soil from raindrop impact, the plant stems obstruct the flow of surface water. As the speed of flow is decreased the erosive potential of the flowing water is reduced. If the speed of flow can be reduced sufficiently then any soil that the water is carrying will also be deposited. Different crops are grown in alternate strips along the contour lines. The crops are chosen so that some part of the field has plant cover at all times. When one strip is susceptible to erosion, for example during tillage operations, the next strip with its established vegetation cover acts as a buffer and reduces surface flow. This system can also be used to build up contour ridges because of the continual deposition of soil in one strip.
As mentioned previously it is very important that adequate cover is provided during periods of high erosive potential. Although the climatic characteristics and growing season in a specific region largely determine whether this can be achieved, the use of multiple cropping systems, and especially strip cropping, greatly assist in achieving this objective. Furthermore, crop rotation and multiple cropping systems, when combined with reduced tillage systems, are one of the most effective ways of increasing soil organic matter levels. Elwell (1992) describes one recently tried system in which soil losses and water runoff have been reduced to very low figures. The system consists of alternating on-contour strips of dense cover crops and row crops, making up an entire rotation planted together on the land between two adjacent contour ridges. The following year the crop strip adjacent to the contour channel moves up to just below the contour bank above it and all crops moves down one strip. Within limits the crop strips vary in width to accommodate the proportion of any particular crop in the rotation. The rotation used was 70% maize, 20% soybeans, 10% finger millet, with the last two planted as cover crops at high density. Land preparation involved shallow ripping to 50 mm on plant lines and into the previous crop residues. Hand tools were used for weeding. Maize was under-planted with pumpkin and cow pea to improve bio-diversity, to spread risk and to suppress weeds. No chemicals, either fertilizer, neither insecticides nor herbicides were used thus minimising inputs other than labour. Yields in good rainfall years were equivalent to conventional tillage systems and in a drought year they greatly exceeded those of conventional systems. The annual soil loss and water runoff from this trial to date on clay soils has to date been 0.5 tonnes/ha and below 2% respectively.

Table ____ (@ Elwell (1992), p 18, table 1) shows the relative soil, nutrient and water losses for different tillage systems on sandy and clay soils. As can be seen the conventional ploughing system resulted in very much higher losses than the reduced tillage systems designed to conserve soil and water. The crop yields of the various tillage systems are discussed in Section 2.5.

Mechanical conservation works are used to supplement the use of tillage, cultivation and management systems to control water erosion in fields where the steepness of the gradient can lead to a severe erosion potential. Depending on the erodibility of the soil and the intensity of the rainstorms this can occur on slopes of 1% and above. Contour ridges, and their associated waterways, are used to reduce the down slope length of the field and hence reduce the amount of runoff passing over cultivated soil in the field and hence reduce erosion losses. The runoff is diverted off the field at non-erosive speeds in contour channels and grassed waterways. The mean amount of water running over the cultivated areas is reduced by a factor roughly equal to the number of contour ridges on a slope. On some very steep lands terracing can be used to both reduce the slope of the field as well as the down slope length of the field, and hence substantially reduces erosion losses.

However some caution is required in the use of conservation works. Firstly, there is a tendency to think that because they are being used that further in-field protection of the soil is not required. This is not the case, as soil lost to the contour channel and waterway is usually lost to the field and is not returned. Secondly, if little soil and water conservation practices are adopted between contours, then the amount of runoff can be great and the concentrated water runoff from the waterways can pose the danger of gulley erosion further down the slope, unless comprehensive conservation works are implemented and maintained over the whole watershed. Some further details of mechanical conservation works are discussed briefly in Section 4.

2.2.2. Wind Erosion

Wind erosion generally occurs in arid and semi-arid regions where precipitation is so low or variable that a crop or cover of residues cannot be maintained on the land. The regions most susceptible to wind erosion on agricultural land are much of North Africa and the Near
East; parts of southern and eastern Asia; Australia; southern South America; and the semi-arid parts of North America (FAO 1978).

Soil erosion due to the action of wind can be very severe and losses of topsoil of over 1000 t/ha have been recorded. Earlier this century in the 1930s the use of inappropriate tillage systems over a period of many years in the semi-arid farming areas of the USA led to serious land degradation. This led to the impoverishment of many farmers and rural societies in the Dust Bowl period.

Wind erosion of soils results in the loss of the fine silt, clay and organic matter from the surface due to the winnowing action of the wind. Under severe conditions this can lead to a substantial decrease in the productive depth of soil as well as severe nutrient losses. This can completely ruin a field with respect to future crop production. Severe wind erosion can also lead to problems resulting from the deposition of the soil removed from fields which can fill ditches, cover roads, bury fences, etc., and require substantial expenditure to rectify the problems.

2.2.2.1. Factors Influencing Wind Erosion

At low wind speeds the wind speed at the soil surface is virtually zero but increases smoothly and rapidly with height above the surface, a condition known as laminar flow. As speed increases the flow becomes turbulent with high speed vortices coming down to the soil surface. Severe erosion can be expected when turbulence occurs because soil particles can then be carried up to higher wind layers. A detailed account of the transport of soil particles, which includes saltation, surface creep, suspension, sorting, abrasion, avalanching and deposition are given by Woodruff and Siddoway (1973). Three main types of soil movement are described below:

- **Saltation:**
  This involves the soil particle being picked up by the wind and carried forwards in a series of short flights interspersed with falling back onto the soil surface. The size of the main particles transported in this manner are between 0.05 and 0.5 mm. The particles are seldom lifted higher than 30 cm and when they fall back to the surface the impact can cause loosening and erosion of other particles.

- **Suspension:**
  This occurs when small particles, generally less than 0.05 mm, lifted by the saltation process are then caught up by the turbulent wind-stream, possibly to heights of 2 to 3 km. Loess deposits are the result of this form of transport.

- **Surface Creep:**
  This occurs when larger particles, generally 0.5 to 1 mm, are displaced by a sliding and rolling motion.

The main conditions necessary for soil erosion due to the action of wind to occur are listed below:

- A dry, loose and fine topsoil.
- A smooth soil surface with little or no vegetative cover.
- A wind that is strong enough at the soil surface to move soil.

Fine sandy soils are extremely susceptible to erosion by wind because there is little cohesion between their soil particles, they dry rapidly and the size of individual particles is small. Other soils are also prone to severe wind erosion when they are dry and loose. Their lack of good soil aggregation and the resultant looseness of individual particles may be due to raindrop impact, freezing and thawing, or tillage. Particles greater than 0.84 mm in diameter are usually considered to be non-erodible by wind. The relation between soil texture, erodibility and wind tunnel losses for the various classes of soils is shown in Table ___ (@ Godwin 1990, p 63, table 2.17). Moist soils are less prone to wind erosion because the moisture increases
the cohesion of soil particles to those below them and also increases aggregation.

Soils with a smooth soil surface are highly susceptible to wind erosion. This is primarily because there is nothing to trap a soil particle once it has started to move. Roughness can be provided by having a ridged surface, a cloddy surface, or a surface with crop residues lying on it. On rough soils the loose soil particles on top of ridges or high points can easily be picked up and transported by the wind, but are likely to fall into furrows or holes when they fall down to the soil surface and are thereafter protected from the wind. After some time this leaves only non-erodible soil aggregates on the high points and further wind erosion ceases. Smooth soil surfaces result from several processes, including, tillage operations that break up surface clods and remove or incorporate surface residues; raindrop impact; freezing and thawing; and erosion itself.

The force of the wind at the soil surface depends both on the wind speeds in the atmosphere as well as on whether any barriers slow down the wind speed at the soil surface. These barriers can be either low in-field ones, such as a standing growing crop, or standing residues, or larger out of field ones, such as wind breaks on the edge of the field. The length of the field down wind of the wind break is of crucial importance and should be as narrow as practicable. Soil movement begins at relatively low wind speeds and progressively increases as wind speed and turbulence increases (FAO 1978). To minimise erosion, therefore, wind speed at the soil surface should be reduced to the threshold value below which no significant erosion will occur (Skidmore and Siddoway, 1978).

2.2.2.2. Estimation of Soil Loss due to Wind Erosion

In the section on water erosion the reasons for the importance of being able to estimate soil loss from a particular field were outlined. The same reasons apply to the estimation of soil loss due to wind erosion.

A generalised equation expressing the relative quantity of wind erosion from a field was first published by Chepil (1959). This model has been developed further by Chepil and Woodruff (1963), and is given below:

\[ E = \text{function of } (ICKLV) \]

Where:
- \( E \) - Potential erosion per unit area per annum.
- \( I \) - Soil erodibility.
- \( C \) - Local wind erosion climatic factor.
- \( K \) - Soil surface roughness.
- \( L \) - Equivalent length of field (maximum unsheltered distance across the field along the prevailing wind erosion direction).
- \( V \) - Equivalent quantity of vegetative cover.

A guide containing the above information in the form of tables and graphs is available for the Great Plains states of the USA in Craig and Turelle (1964). The extent to which this information can be transferred to other regions needs to be evaluated by local research personnel. Tillage has a direct bearing on factors \( I, K \) and \( V \), through its effect on soil cloddiness, soil roughness and vegetative cover.

2.2.2.3. Control of Wind Erosion

In those regions prone to wind erosion its control is one of the main criteria in the selection of appropriate tillage, cultivation and management systems. Many of the methods
used to control wind erosion are the same as those used to control water erosion. This particularly applies to those techniques used to increase soil aggregation and to provide cover to the soil through crop cover or the use of crop residues. However some techniques may be mutually exclusive, for example, ridging to control water erosion has to be done slightly off-contour, whereas ridging to control wind erosion is done with the ridges perpendicular to the prevailing erosive winds.

The main means of control of wind erosion are directly related to the factors influencing erosion discussed previously and are listed below and then discussed:

- Increase surface soil aggregation to reduce the susceptibility of particles and aggregates to being transported:
  - Increase soil organic matter content.
  - Minimise tillage operations and avoid those that excessively fragment soil structure.
  - Raise aggregates to the surface and bury finer particles.
  - Protect soil surface from raindrop impact:
  - Retain crop residues on surface.
  - Increase crop cover.
- Increase soil moisture content to reduce the susceptibility of particles and aggregates to being transported:
  - Increase water infiltration.
  - Reduce water runoff.
  - Reduce soil water evaporation.
- Increase surface roughness to trap particles and aggregates once they have started to move:
  - Increase clodliness and ridge roughness.
  - Retain crop residues on the soil surface.
- Reduce surface wind speed to reduce its capacity to transport particles and aggregates:
  - Increase surface roughness.
  - Increase in-field wind barriers:
  - Increase growing crop cover.
  - Retain standing crop residues.
  - Increase out-of-field wind barriers:
  - Provide suitable wind breaks.
  - Reduce length of field below wind breaks to suitable length.

The problem of a dry, loose and fine topsoil can often only be partially resolved. As mentioned previously fine sandy soils are extremely susceptible to erosion by wind, because there is little cohesion between their soil particles, they dry rapidly and the size of individual particles is small and are thus easily transported by the wind. Although increasing the soil organic matter content will increase aggregation to some extent in these soils, it will not in itself be sufficient to protect them. Whereas, the retention of crop residues on the surface will increase soil roughness and also increase their moisture content by increasing water infiltration and reducing evaporation, as well as increase organic matter content. The clay particles in soils are an important factor in the provision of cohesion between soil particles, and hence in aggregation. On some sandy soils where the clay particles have been leached to lower layers they can be brought back to the surface by deep ploughing in order to promote improved aggregation and improve the nutritional characteristics of the topsoil. Unger (1984) summarises this research and provides a means of calculating the tillage depth required to increase clay content of the topsoil to a specific level. It was found that at least 8% clay content is needed in the surface layer of sandy soils for subsequent tillage to result in clods that resist wind erosion. However, it was found that this remedial action may not be sufficient in itself and should be supplemented with good supporting practices. Some shallow tillage operations, such as harrowing with tined implements, can be used to bring larger non-erodible aggregates up to the surface and to bury smaller soil particles.
The soil particle sizes of silts and clays are much smaller than sands and if these soils are not cultivated properly they may be prone to more severe wind erosion than sandy soils. They can be better protected than sandy soils by increasing soil aggregation. As soil aggregates are broken down by raindrop impact the retention of crop residues is an important means of protecting these soils. This measure also assists in increasing roughness and moisture retention and improvement in organic matter content. Increasing the crop cover by selecting appropriate cultivation and management practices is also an important means of protecting soil aggregates on the surface.

Minimising tillage operations is another means of minimising the destruction of soil aggregates. Furthermore those tillage operations that result in an excessive destruction of aggregates should be avoided. Generally those implements that have a highly abrasive action destroy aggregates and result in a higher proportion of individual soil particles. The main implements in this category are those using discs. Rotovators also leave a high proportion of individual particles because they tend to pulverise the soil. Tillage should also be carried out when the moisture content of the soil is appropriate. Tillage operations carried out with the purpose of forming non-erodible clods on the surface should generally be carried out when the soil is fairly moist.

A dry surface is more prone to wind erosion than a moist surface because the moisture increases cohesion between soil particles. It is therefore desirable to increase or maintain high moisture levels at the surface to reduce erosion losses. This can be done through increasing water infiltration, reducing runoff and reducing soil water evaporation. These aspects have been covered extensively previously. However, it should be noted that in many regions prone to wind erosion the annual precipitation is so low that the proportion of the time that the topmost layers of the soil can be kept moist is also very low. This means that moisture conservation can not be used as the main means of controlling wind erosion in these regions. However, because moisture conservation also helps in improving the organic matter content of the soil and hence its aggregation, it is an important constituent of any strategy to reduce wind erosion.

Producing a rough surface is another important means of reducing wind erosion as the moving soil particles are trapped in the hollows when they fall back to the surface. A rough surface can be produced either through the retention of crop residues on the surface or through the use of appropriate tillage operations and implements. Tables ____ (@ Godwin 1990, p 57, table 2.12) and ____ (@ Godwin p 57, table 2.13) listed the cloddiness and ridge roughness produced by various tillage implements. It should be noted that whereas the mouldboard plough produces the maximum cloddiness of the implements listed, it also produces one of the lowest values for ridge roughness. From a study carried out on the effect of various primary tillage practices on estimated soil loss, see Figure ____ (@ Godwin p 63, fig. 2.30), it appears that cloddiness was generally of more importance than ridge roughness in reducing wind erosion. Roughening bare erodible soil can reduce soil losses, but the greatest impact of tillage is when increased oriented roughness is combined with increased cloddiness, as shown in Table ____ (@ Godwin p 60 table, 2.15). The effect of ridge height on soil loss is shown in Figure ____ (@ Godwin p 60, fig. 2.28). As can be seen, a ridge of 60 mm reduces soil loss to less than 20% of that lost from a flat surface. Increasing the ridge height above 60 mm has little effect on further reducing wind erosion losses. When ridges are used to control wind erosion they should be at right angles to the prevailing erosive wind. In situations where these are not just off-contour and where water erosion is a potential problem, then ridges should not be used to control wind erosion as their presence could result in worse water erosion problems.

The effect of soil cover on reducing soil loss due to wind erosion is shown in Figure ____ (@ Godwin p 61, fig. 2.29). The cover can be any form of non-erodible material, usually crop residues, but also includes stones and non-erodible soil clods. As can be seen the relationship is very similar to that for water erosion. Again, a 30 % cover is the generally recognised
minimum, and this results in a soil loss ratio of 0.2. Because different soils are prone to different amounts of potential erosion, from the same erosive force, different levels of protection are required to limit erosion to the same amounts. The amounts of residues required to reduce erosion to tolerable levels, as defined for the USA, for some different soil categories are shown in Table ____ (@ Godwin p 59, table 2.14). It will be remembered from the discussion on the use of models for the estimation of soil loss, that one of the important advantages of being able to estimate soil loss was to set a limit on the loss of soil, the tolerable level, and to then devise practices that would reduce erosion to this limit. An important point to note is that different types of crop residues have very different characteristics in the amount of protection they provide. The percentage cover given by different weights of some standard crop residues was given in Table ____(@ Godwin p 61, table 2.16). It will also be noted that standing residues afford more protection from wind erosion to the soil than flattened residues. The mechanism by which standing residues reduce wind erosion is by reducing surface wind speed, whereas flattened residues reduce wind erosion partly by providing a roughened surface and partly by reducing wind speed, but the latter to a much lesser extent than standing crops.

The reduction of surface wind speed is a very important means of controlling wind erosion. Reduction of wind speed can be achieved through the use of in-field barriers or out of field barriers, or by increasing surface roughness, which has already been discussed. In-field barriers can be either from growing crops or crop residues. As shown in Table ____ (@ Godwin p 59, table 2.14) above, standing crop residues are roughly twice as effective at reducing wind erosion when compared to flattened residues. This is because the height over which they are effective provides a much more efficient barrier to the wind at the soil surface than flattened residues. Even where the retention of standing residues is not feasible for use with a particular tillage or cultivation system, their retention during a dry fallow period prior to planting may be highly desirable, if this period coincides with a period of high wind erosive potential.

As with the control of water erosion, the use of a growing crop to provide protection requires that the crop is growing and is of sufficient stature during the periods of high wind erosion potential. In arid areas where the amount of vegetative cover produced is low and where the crop grows for a short part of the year the use of this control on its own is very limited. However, used in conjunction with the retention of residues on the surface and other controls it is an important component of a whole conservation strategy. The use of multiple cropping systems, and especially strip cropping, can be very effective. These systems are discussed in Section 3.2.2.3. When it is desirable to grow an erosion-susceptible crop, for various economic or other reasons, then by using a strip cropping system the erosion susceptible crop can be grown in alternate strips with erosion-resistant crops, traversing the prevailing wind direction. The widths of these strips depend upon the soil type and the minimum widths range from 6 to 8 m on loamy sands, 30 to 70 m on sandy loam to 130 m on silty loam, Krause et al (1984).

The provision of out-of-field wind barriers is another important control in the reduction of surface wind speed. This control must be used in conjunction with limiting the length of the field downwind of the break to a suitable distance. Some general points can be made: Firstly, the distance downwind of the windbreak over which the surface wind is reduced is a function of the height of the windbreak. Hence, if windbreaks are used to control wind speed then the maximum length of the field downwind of the windbreak should be determined by the height of the windbreak. Secondly, it is important that the windbreak is not too dense and that it allows the wind to pass through it, and hence does not in effect provide a solid barrier to the wind. If it does provide a solid barrier then it can induce strong horizontal vortices over the field which can bring wind down to the soil surface, which has a speed much higher than the surface wind speed, would be without the use of the solid windbreak. This is because wind speed initially increases rapidly with height above the surface until it reaches a limit well above the earth's surface, and thus the wind speed at treetop height is much faster than at ground level. The reason for this speed profile is because the earth's surface acts as a resistance to the movement of the wind. If the windbreaks allow some wind through them then they still act as a
barrier to the wind, and slow its speed, but will not induce strong horizontal vortices. The tree shape and whether it is in leaf at the time of highest wind erosive potential are important factors in the selection of suitable trees for windbreaks. The water demand of the trees and a number of other factors are also important considerations.

2.2.3. **Formulation of Programmes for the Control of Soil Erosion**

Due to the fundamental importance of the control of soil and nutrient loss due to water and wind erosion for sustainable crop production it is vitally important that a comprehensive approach is undertaken to limit erosion. Whilst specific techniques to control water and wind erosion have already been described, the effectiveness of these measures will be greatly enhanced if they form part of a well thought out comprehensive programme. As this is a substantial subject in itself only a brief overview will be given in this report. If no comprehensive strategy for soil and nutrient conservation has been developed for a particular country, then it is highly desirable that the relevant authorities establish a broad group of people to develop one and then oversee its implementation.

As Unger (1984) points out a key component of a comprehensive conservation programme is the introduction of appropriate land use measures. Under such a programme, for example, crop production would be limited to such areas where erosion is at acceptable levels or where erosion can be maintained at or below acceptable levels through the use of effective erosion control practices. Likewise, lands not suitable for crop production would be used for grazing, forestry or wildlife etc., as appropriate to the capability of the land, and managed such that no land degradation occurred.

Before appropriate land use measures can be introduced, the land resources of a country along with their potentials for use and degradation must be thoroughly understood (FAO 1977). The starting point for evaluating land resources is a field survey that locates and identifies soils by mapping units. From the soil surveys, a land capability classification is then prepared and related to the soil mapping units (Constantinesco 1976). In the system developed by the Soil Conservation Service of the US Department of Agriculture, eight land capability classes are recognised. These classes given in Table ____(@ Unger 1984, p 30, table 2) are based on the suitability of the land for use without permanent damage. In establishing the classes, factors considered were the risks of land damage from erosion and other causes, and the difficulties in land use due to physical land characteristics and climatic factors (SCSA 1982). Other classifications could be based on other types of land degradation, e.g. desertification and salinization. Land use planning systems require large government departments to implement and enforce them and although expensive they are necessary to maintain agricultural production at levels high enough for a country to be self sufficient in food over the long term.

Prior to giving a very brief overview of strategy formulation for conservation, some examples of problems likely to occur in the implementation of conservation programmes will be given. One of the main problems is the conflicting requirement for the use of crop residues. Even where the amounts of residues are initially adequate there are many traditional alternative uses for the residues. These include primarily fodder and fuel, and to a lesser extent raw materials for the manufacture of various items. Furthermore, in many arid and semi-arid areas the amount of vegetative matter grown per hectare, and hence available as crop residues is so low that its retention, although beneficial, is not adequate for use as the main means of the control of erosion and the maintenance, or improvement, of the nutritional status of the soil. Alternative tillage systems may be considered, but it may be found that the only tillage systems that reduce soil loss to acceptable levels require excessive energy inputs or the use of equipment that is not locally available. Choices then have to be made over whether it is feasible to increase draught power availability to provide the extra energy input required, and whether the required equipment can be provided locally, or whether the traditional agricultural
practices that result in the lack of adequate crop residues can be changed. The latter option may involve the fencing of fields to keep grazing livestock out, the improvement of grazing lands by paddocking, growing fodder crops, or at the other extreme, consideration of social intervention such as introducing banks into rural areas to reduce the need to use cattle as a capital resource and so reduce the grazing pressure on the land. The improvement of grazing through paddocking may be justified more on the basis of increasing carrying capacity rather than keeping livestock off the arable lands. An additional consideration is that prior to encouraging the use of crop residues on lands to control erosion, it is essential that farmers have the resources and management ability to control the increased level of crop pests associated with the use of residues. If these are not available then plans to provide them need to be drawn up and then implemented. From the foregoing it can be seen that a comprehensive conservation programme requires the consideration of a many alternative options, and that it includes components of research, planning, training, extension and the coordination of work undertaken in a number of disparate technical fields.

There are some very formal procedures involved in the formulation of a strategy to achieve a series of objectives. Although it is initially perhaps a rather daunting exercise, once the procedure is understood, it greatly facilitates a thorough analysis of the issues involved and how to lay out and implement a plan to achieve the desired objectives. The formulation of more limited programmes to achieve a less wide ranging set of objectives can also beneficially use the basic strategy formulation procedure. One formal technique used for the formulation of projects is the Objective Oriented Project Planning system as used by GTZ, which is similar to the USAID system, and this can also be used for the planning of programmes.

The starting point for strategy formulation is generally a review of government policy documents and the government's National Development Plan. These plans generally state what needs to be done. However, where these plans are not sufficiently specific then the strategy document should specify what needs to be done. The strategy then describes how it is to be done, by whom, when, and in what order. As Gifford (1981) points out the strategy document is a blueprint for action, a procedural manual for the daily guidance of all those inside and outside government service that have to make a decision.

The first step is to set up a team of personnel to formulate the strategy or programme. It is highly desirable that the key people in this team are later also responsible for coordinating the implementation of the strategy. Senior personnel from the key ministries and organisations involved in the programme should be in the team. If there are substantial financial implications involved in the strategy then it is important that the Ministry of Finance is involved at a senior level.

The overall goal that the strategy is set up to achieve is divided into a number of subsidiary objectives, which, if all of these were achieved would mean that the overall goal was achieved. For each of these objectives a sub-programme is drawn up to achieve them. The sub-programmes include the activities required, the responsible organisations involved, the period required for the activities to be completed, and an indicator of achievement.

At the outset it should be appreciated that the amount of work involved in the formulation of strategies is large and that it will initially primarily involve senior personnel in key ministries. It can therefore not be undertaken lightly. However, the benefits are large, as the formulation procedure forces a rigorous analysis of the problem, its solution, and all the associated implications in their entirety. Too often when complex problems are tackled key components of the problem or solution are overlooked, which seriously undermines the time and money invested in trying to solve the problem. If the formulation of a full strategy is not initially possible it is still worthwhile formulating smaller action programmes, using the strategy formulation procedure but with narrower objectives, that could at a later date be incorporated into a fuller strategy. If correctly formulated the rigour involved in the procedure will ensure that resources are not wasted.
2.3. CLIMATE

The climate has a major effect on crop production and is one of the most important factors to be considered in the selection of tillage systems for crop production. There are two main reasons for this. Firstly, the climate determines some of the main characteristics of the soil, primarily through the long term leaching effect of precipitation on the soil. Secondly, there is the direct effect of the various climatic factors on the growing crop and the tilled soil. These latter factors will be discussed initially and this will be followed by a discussion of the classification of the major climatic zones of the world and the different objectives of tillage in these zones.

2.3.1. Climatic Factors

The main climatic factors are precipitation, temperature, radiation and wind. The ways in which these parameters affect soils has already been discussed in detail in Section 2.1, but it is considered important to discuss these from the perspective of the climate. Extensive use is made of the information presented in Unger (1984).

2.3.1.1. Precipitation

The amount of precipitation, its variability and distribution are the most important climatic factors affecting the choice of crop and tillage system. The distribution of precipitation is important both in terms of the length of the rainy season and its distribution during that season. The tillage system chosen should be adapted to the level of risk of low or high annual precipitation as well the risk of a short season and short-term droughts within the season.

Detailed knowledge of an area from experienced local farmers and agricultural workers is the main source of information of the limitations of farming practices in an area. In addition to these sources many countries have been mapped in terms of agro-ecological regions, based largely on the amount and distribution of precipitation and on soil type. These maps are extremely useful for assistance in choosing crops and tillage systems. General meteorological information is also usually available for a number of locations within a country. However, it is desirable that this is presented in a format immediately useful to workers in the agricultural field. The main details required are listed below:

- Mean annual rainfall and its variability. This information will largely determine the type of crops and tillage systems that can be considered.
- The probability of the rainy season being greater than or equal to the season required for the crop, determined for all crops and main cultivars. This information can also be expressed in terms of the number of poor seasons to be expected out of say five for each crop. This information will largely determine the feasibility of growing certain crops or cultivars in a specific location. It will also determine the type of risk limitation strategy adopted by farmers, depending on their resource base. This latter aspect will be covered in a later section.
- The probability of general short-term droughts. This information will affect both the type of crop chosen and the level of moisture conservation required of the tillage system.
- The probability of a short-term drought at a critical period during the maturation of the crop, e.g. tasselling in maize. If droughts are likely at critical periods then, if possible, it is desirable to shift the start of the cropping season or choose another crop.

In regions where there is a deficiency in precipitation, either because of low mean rainfall or short-term droughts, then one of the prime objectives of the tillage system used is to
improve the conservation of water for subsequent use by the plants. Three factors are involved in this; water runoff during precipitation should be reduced, evaporation of water from the soil surface and evapotranspiration from weeds should be reduced, and the water holding capacity of the soil should be increased. The means of achieving these aims have been discussed in detail before and are not repeated here.

In tropical and sub-tropical regions where precipitation is excessive there is still often a fairly high probability of short-term droughts during the rainy season. Depending on the probability of these short-term droughts the conservation of water for favourable plant growth during these periods may still be an important objective of tillage. A tillage system would then need to be selected that balances the requirements of dealing with the excess water as well as the need to conserve water in case of short-term droughts.

Where excess water is a long-term problem then surface and sub-surface drainage schemes may be required as part of the overall system. Lined sub-surface drains are a major undertaking whereas unlined mole-drains can be installed in soils with a fairly high clay content at a much lower cost using a tractor drawn subsoiler fitted with a mole and expander. Surface drainage can be facilitated where necessary by ridging off-contour and planting on the ridges. The slope of the furrows should not be excessive, as a high water speed in the furrows will result in erosion. Details of these operations are given in Section 5.

Where excess water is an occasional problem, e.g. at planting time, then ridging or ploughing to expose wet soil or to bury surface residues can be used to hasten soil drying. If excess water is a long-term problem then crop residues should generally not be left on the surface as they reduce runoff.

The tied-ridging system can be a good system to use in regions where precipitation may at times be excessive and at other times deficient. The system is very good at reducing water runoff during light showers and the ties can overflow during heavy showers. If waterlogging becomes a problem then the ties can be broken to improve surface drainage. Even with water sitting in the furrows the surface roots of the plants on top of the ridges are not subjected to waterlogging problems. The tied-ridging system is also extremely efficient at reducing soil erosion when it is installed correctly.

The amount and intensity of precipitation is also one of the most important factors determining the risk of erosion, which in turn is a very important factor in determining the choice of tillage systems.

2.3.1.2. Temperature

The prevailing temperatures strongly influence the selection of crops to be grown in a region as well as the crop production methods. Although tillage systems have little or no effect on air temperature they can be used to increase or decrease soil temperatures.

In tropical and subtropical regions low temperatures are seldom limiting factors except where the frost-free growing season is relatively short. In these cases a few extra days of growing season can make it possible for the crop to mature before the onset of frost. Tillage systems can be selected that increase soil temperature to enable earlier planting, providing precipitation is not a limiting factor at the time, and so extend the growing season. Mulches on the soil surface moderate the day and night temperature fluctuations of the soil, and delay the warming of the soil at the start of a warmer season. The selection of a clean or non-mulch tillage system will generally result in a faster rise in the soil temperature as air temperatures increase. Ridging a soil will generally result in an increased seedbed temperature in the peak of the ridge as compared to a completely level seedbed.
High temperatures affect the crop by increasing evaporation of water from the soil surface thereby reducing the amount of water available to the plant in precipitation-deficient regions. Tillage systems that leave crop residues on the surface will reduce extreme soil temperatures during the day and so reduce evaporation.

2.3.1.3. **Radiation**

Since solar radiation is the energy heating the soil, the soil temperature varies with geographic location, i.e. it is higher in the lower latitudes and lower in the higher latitudes. Soil temperatures also vary at a specific location because the solar energy arriving at the soil surface is determined by the steepness and direction of any slope.

Tillage affects the radiation balance of the soil, i.e. the soil's absorption, storage and reradiating of heat from the sun, mainly through its effects on soil colour and water content, its slope relative to the sun and through crop residues left on the surface. The radiation balance directly affects water conservation through its affect on temperature. As balance of radiation remaining in the soil increases so its temperature increases.

Light-coloured surfaces reflect radiation whereas dark ones absorb it. Thus a freshly tilled, rough moist soil will absorb more radiation than a smooth, dry soil. On sloping soils, absorption is greatest when the sun is perpendicular to the slope. Light coloured crop residues on the surface of dark soils will reduce the absorption of radiation as compared to the bare dark soil. As residues age and darken they reflect less radiation and hence absorb more. Standing residues also reflect less radiation than lying ones.

2.3.1.4. **Wind**

Wind is a major determinant of the choice of tillage system only where it causes soil erosion. However wind also affects the soil-air microclimate, as evaporation of standing water on the soil surface increases as wind speed increases. Surface wind speed can be reduced by leaving crop residues on the soil surface in lands prior to the establishment of the crop. Once the crop is substantially higher than the residues then the crop itself will have more effect than the residues on reducing surface wind speed. When there is no standing water on the surface then the capillary action of the water through the soil to the surface may have a more controlling effect on the rate of evaporation than the wind speed.

2.3.2. **Tillage Objectives in the Major Climatic Zones**

As previously mentioned the climate has a major effect on crop production and is one of the most important factors to be considered in the selection of tillage systems for crop production. The climate and weather particularly affect the following:

- The soil water balance throughout the year, both during and between the periods that the crop is grown.
- The duration of the crop growing period, which is limited by water deficits and/or low temperature.
- The soil temperature.
- The soil microbiological and chemical processes.

Based on the above, Krause et al (1984) considered several climatic zones, viz. the temperate humid climates; the tropical arid climates, with winter and summer rainfall patterns; and the humid and sub-humid tropical climates; and drew up tillage objectives for these zones. The following sections are based on their analysis.
2.3.2.1. **Soil Tillage in Temperate Humid Climates**

The temperate zones occur between the tropics and Polar Regions. The humid regions are those in which the annual precipitation exceeds evaporation. Rain intensity is generally low. The crop growing period, or vegetation period, is restricted by low temperatures, and in some cases also by insufficient light. During the cooler season the rate of decomposition of soil organic matter is low due to the reduced activity of the soil micro-organisms, and the rate of evaporation is also low. Freezing and thawing due to the action of frost improve the structure of exposed soil.

As precipitation exceeds evaporation, the soil water descends into the subsoil carrying with it dissolved salts and small soil particles. These can accumulate into dense layers which are impermeable to water and partially or fully impenetrable to plant roots. This tendency increases with increasing precipitation, increasing soil texture coarseness and with the occurrence of natural soil boundaries. Because of the leaching effect of the water, soils in these regions tend to be acidic.

The time available for tillage operations is comparatively long but depends on the crop rotations used. Heavy soils, i.e. those with a high clay content, are an exception. Due to their high water retention characteristics, the moisture levels suitable for tillage only occur for short periods. Primary tillage operations can be performed at the end of the growing season and during the cooler season, thus increasing the period over which operations can be performed prior to the start of the next season. This is because tillage does not markedly increase the decomposition rate of soil organic matter due to the low temperatures.

The following objectives generally apply to tillage in the temperate humid regions:

- Rectify any damage to the soil structure, which may have occurred during the cropping season, e.g. compaction, by the use of deep tillage and frost action.
- Return the leached small soil particles, i.e. the clay minerals and nutrients, back to the topsoil by inverting the soil. The frequency of this operation depends on the level of leaching and is not required frequently on heavy soils.
- Control weeds as they compete with the crop for nutrients, and also water during short term droughts. Inversion of the soil with a mouldboard plough is the best mechanical means of controlling weeds.
- In regions where low soil temperatures limit the growing season, speed the warming of the soil by using clean tillage systems and tilling at the start of the growing season.
- Burry crop residues in clean tillage systems, for pest control and to facilitate ease of use of implements due to large amount of crop residues in humid regions.
- Control soil erosion by use of appropriate tillage systems in areas prone to soil erosion.

The research in soil tillage in the temperate humid regions is primarily geared towards saving energy and costs.

2.3.2.2. **Soil Tillage in Tropical Arid Climates**

The tropical and subtropical arid regions occur mainly between latitudes 10 and 25 deg. north in India, Africa, and Southeast Asia. There are also important semi-arid regions south of the equator in eastern and southern central Africa, Australia, Mexico, Argentina, and northeastern Brazil. Arid climates, and to a lesser extent semi-arid climates, are characterised by a deficit water balance. The annual precipitation is exceeded by the annual evaporation, as a result of the low humidity, high temperatures and wind. A positive water balance, i.e. a humid climate, may temporarily exist during the rainfall season. Rain occurs during specific periods only and two basic climatic types can be classified, viz., summer and winter-rainfall areas. The length and timing of the rainy season or seasons and the intensity of rainfall is dependent on
The amount and frequency of rainfall is highly variable and considerable annual deviations from the long term mean occur. Intermittent and unpredictable dry periods occur during the wet seasons. Tropical climates are also characterised by warm year round temperatures. Subtropical climates are generally cooler and frost may occur at night during the winter.

During evaporation the soil water, with dissolved salts, is transported upwards to the soil surface. The salts crystallise on or near the surface as the water vaporises. A deficit water balance may therefore result in the formation of alkaline soils with a high concentration of salts in the upper layers or on the surface.

The main limiting factor to crop growth under these climatic conditions is water. The yield of a crop in any one year is largely determined by the amount and distribution of precipitation in that year. As previously noted considerable annual deviations from the long term mean occur and total crop failures are fairly common. This not only results in a loss of seed, fertilizer and labour inputs, etc., but also results in little or no surface protection for the soil, leading to potentially high erosion losses from the soil. As water is generally the limiting factor in these regions, tillage systems should be selected which maximise water infiltration and storage, and minimise water runoff and evaporation. This would also minimise erosion. In addition, competition for water from weeds should be kept to a minimum. In areas with low rainfall the soil is seldom moistened to depths of more than 30 cm and so shallow soil tillage is recommended. Proper land use planning procedures should also be adhered to and where this is not possible then even more stringent erosion control measures need to be applied.

The growth period for plants in arid areas is generally short and limited by the start and end of the rains. Once the rains end and the soil dries the plants start to ripen and growth ceases. The use of cultivars whose season length is less than or equal to that of the expected season is important. Crops should be planted just before or after the start of the first rains to maximise use of the growing period. A delay in planting after the start of the rains results in an initial loss of yield of 5% to 10% per week, or even higher in some regions. Generally, the weekly percentage loss increases the longer planting is delayed.

As previously discussed tillage results in an increase in the rate of decomposition of organic matter especially when the temperatures are high. This is because loosening the soil increases the air and oxygen supply and, together with high temperatures, increases the activity of the micro-organisms living in the soil. The loss of soil organic matter results in a rapid deterioration in the soil's capacity to retain nutrients and water and also diminishes the soil's mechanical properties. Deep tillage also results in a direct loss of soil water to the atmosphere by exposing the moist subsoil. From the foregoing it can be seen that in regions where a significant proportion of water in the soil can be carried over from the end of one season to the start of another, then deep tillage at the end of a season is not desirable as this will result in a loss of plant available moisture at the start of the next season. In these situations it is desirable to undertake the primary tillage operations immediately before planting at the start of the rainy season, in order to maximise the water available to the germinating seeds and seedlings. The soils in many arid areas are extremely hard when dry and, when draught animals are used, can only be ploughed after the first rains. This situation is made worse by the draught animals being in their poorest condition at the end of the dry season due to a shortage of fodder. Valuable time at the start of the growing season is therefore lost preparing the fields. There is therefore generally very little time for tillage operations in arid regions. Hence, tillage operations require a much higher level of efficiency in their execution in arid regions than in temperate areas, if losses due to a delay in planting are to be kept to a minimum.

In some regions the dry season is such that very little soil water is left in the topsoil at the start of the next season, immaterial of the timing or type of tillage operation used at the end of the season. In these regions it may be desirable to carry out primary tillage at the end of the season, because the soil moisture levels facilitate tillage, the draught animals are in good
condition, and the possibility of timeliness of planting for the next season is improved. Furthermore, although autumn ploughing will result in the loss of some moisture from the soil, the early preparation of the soil will increase the infiltration rate of the soil for the first rains and this may more than compensate for the loss of moisture in the autumn. The choice between autumn and spring primary tillage depends firstly, on the amount of water in the soil in the autumn and what proportion of it will last until the next planting season and secondly, on the changes this requires to traditional cultivation practices.

The following objectives generally apply to tillage in the tropical and subtropical arid and semi-arid climatic regions:
- Maximise total water infiltration and water holding capacity.
- Minimise soil water evaporation.
- Control weeds to reduce competition for water.
- Maintain good levels of soil organic matter.
- Control soil erosion.

The arid climatic regions can be divided into winter and summer rainfall regions and the means of achieving the above objectives varies to some extent for these two regions. These will be discussed in the following two sections.

A. Soil Tillage in Winter Rainfall Areas

The regions with a winter rainfall climate, or Mediterranean climate, occur along the length of the Mediterranean, and on the western coasts of all continents between the tropics and latitudes 40 deg. north and south where there are no major mountain barriers separating the land from oceanic winds, e.g. western and southern Australia, California, Chile, and South Africa.

Winter rainfall areas are those in which the rainy season and thus the main vegetation period occurs during the cooler winter months. The winters are generally mild while the summers are hot and dry. However, in some regions the temperatures are sufficiently low to affect the development of cultivated plants. The intensity of rainfall is generally lower than that in the summer rainfall regions and so the risk of erosion is also generally lower. Short-term droughts are fairly common at the start of the rains, but these pose less of a problem for crop growth than they do in summer rainfall areas as the evaporation rate is lower.

In those areas where soil moisture in the plant root zone can be carried over from one rainy season to the next then primary tillage, if it is to be carried out, should be done shortly before or at the beginning of the rainy season, and not at the end of the rainy season. This is because of the high rates of evaporation during the long hot dry season. Furthermore, inversion of the soil is generally not desirable as this causes moisture losses when the subsoil is moist. Pulverization of the soil should be avoided. Shallow tillage systems should be used at the end of the wet season to reduce evaporation by breaking the capillary connection between the surface and subsurface layers. In regions prone to wind erosion crop residues should be left on the land to protect the soil during the long hot dry season, and tillage should aim at creating a coarse aggregate surface by bringing non-erodible clods to the surface. The use of conservation tillage systems in these regions is highly desirable providing they can be properly managed.

B. Soil Tillage in Summer Rainfall Areas

These areas are characterised by precipitation occurring in the hot season. Evaporation losses are at their maximum during this period and short term droughts pose a serious problem for crop production. Although these areas generally receive more rain than the winter rainfall areas, the short term droughts and high evaporative losses during the growing season mean that water conservation is the prime tillage objective. Weed growth is also high during the
growing season and especially at the start of the growing season due to the high temperatures. As they compete with the plants, and especially young plants, for water and nutrients their control is very important.

Rainfall is frequently of the convective type, i.e. thunderstorms, in which the rainfall intensity is high and the raindrops are large and have a high kinetic energy. As discussed in Section 2.2.1.1 this results in a high water erosion potential. The control of water erosion is therefore of prime importance in these areas.

The rainfall seasons are generally short and the timeliness of early planting at the start of the season is very important. As the dry season occurs during the cooler months of the year primary tillage carried out at the end of the season will generally not result in the loss of as much moisture over the dry season as in winter rainfall areas. However, in many areas evaporation during the cooler season is still so high that carrying out primary tillage at the end of the season will result in a loss of most of the water in the plant rooting zone. Shallow tillage to reduce evaporative losses during the dry cool season should be carried out when moisture can be carried over to the next season.

The characteristics of the arid summer rainfall climatic type impose more conflicting requirements on tillage than other climatic types and compromises depending on individual situations have to be found. For example, to increase total water infiltration the soil may need to be loosened to an appropriate depth to increase porosity and holding capacity. However, this increases aeration and together with the high temperatures increases microbial activity and leads to a reduction in soil organic matter. This leads over time to a reduced water and nutrient holding capacity of the soil, reduced porosity due to reduced aggregation and increased susceptibility to erosion. The retention of crop residues on the surface may overcome both of these conflicting problems but is frequently not available in sufficient quantities in these areas to meet these needs, as already discussed. The tied-ridging tillage system may also be a solution as it is an excellent system for reducing runoff and maximising infiltration. However, it is usually used as a clean tillage system with minimal returns of crop residues and the organic matter content of the soil is depleted under these conditions. This tillage system together with others will be discussed more fully in Section 3.1.

2.3.2.3. Soil Tillage in the Humid and Semi-humid Tropical Climates:

The humid and semi-humid tropics are located between 6 to 8 deg. north and south of the equator. The rainfall pattern consists of a principal and a secondary rainy season and the air humidity is high from the start of the first to the end of the second rainy period. Temperatures are high and deviations from the annual mean are less than the daily fluctuations.

Rain forests are the natural vegetation in these regions. Mineralisation rates are very high and the nutrients required for plant growth are held in the abundant decomposing plant remains on the forest floor. If the natural vegetation is removed the source of soil nutrients is removed with them. The soils are generally very shallow and highly prone to erosion if the natural vegetation is removed. Shifting cultivation is traditionally practised in these areas, where a field is cleared and cropped for 2 to 3 years, and then left to recuperate for 10 to 15 years. The marked decline in yield after 2 to 3 years is due to the rapid decomposition of the soil organic matter due to the high temperatures and abundant water. From a conservation point of view this practice is acceptable provided adequate fallow periods are allowed for soil recuperation, and provided population pressures are low so that only a small proportion of the forest is cleared at a time. These aspects are discussed further in Section 3.2.1.1. The pH value of these soils may be as low as 4 to 5.

Sustainable crop production is possible on these soils only when the pH value and the
organic matter content can be increased and then maintained at acceptable levels. Lands often have to be drained. As the soils are prone to erosion and because of the high rainfall and its intensity tillage systems that protect the soil should be used. The retention of crop residues is desirable as it both protects the soil and maintains soil organic matter content. However, due to the high temperatures and abundant water supply weed growth is a serious problem and often leads to the failure of minimum tillage systems. Crop rotations and the incorporation of pulverised crop residues can be used to increase soil organic matter. Appropriate crop rotations and intercropping can also be used to protect the soil from raindrop impact.

Multiple cropping and serial cropping management systems are common in these regions due to the uniform climatic conditions. This requires that tillage operations are carried out efficiently and speedily for the next crop. Due to the high rainfall the soil will often be excessively wet when the tillage or harvesting operations have to be carried out and this leads to damage of the soil structure. Because of this it is very important to select tillage systems that minimise the number of operations.

The following objectives generally apply to tillage in the humid and semi-humid tropical climatic regions:

- Control of soil erosion.
- Maintenance of soil organic matter.
- Control of weeds.
- Improvement of soil structure following compaction.

2.4. AGRONOMIC FACTORS

The main agronomic factors to be considered when selecting tillage systems include the following: the crop to be grown and its specific requirements, e.g. soil water, aeration, planting and root zone depth requirements; weeds, pests and diseases; and the effect of the tillage operations and systems on yield. Some agronomic factors only marginally associated with the selection of tillage systems, but closely associated with cultivation, will also be covered in this section. Cultivation and management systems will be discussed in Section 3.

2.4.1. The Selected Crop

This section will deal with the main factors that need to be considered when selecting a tillage system to suit a particular crop. It will also deal with some general agronomic aspects related to tillage systems.

At this stage it is worthwhile emphasising that generally the tillage system is chosen to suit the crop and not visa versa. The selection of the crop in the first instance is based on a large number of factors, including; the demand for the produce, either for use within the household or for sale on the market; the local climate, in terms of amount of precipitation, its distribution and reliability, season length, day and night temperatures, erosive potential; availability of required inputs, including financial, suitable land, agronomic, labour, implements, servicing facilities, etc.; soil type; stage in crop rotation; potential weed, pest and disease problems; farmer's knowledge of required management system and access to extension advice; availability of storage, transport and marketing infrastructure; etc.

However, in some cases the crop may be chosen to suit the tillage system. If for example, due to overriding considerations of soil and water conservation the use of a conservation tillage system with the retention of crop residues is considered very important, then a crop may be selected for use in a rotation with the most desirable crop, on the basis of its compatibility with the tillage system. The crop may, for example, be chosen partly on the basis that it is resistant to pests that inhabit the crop residues of the previous crop, and in this sense the crop is chosen to suit the tillage system, as the retention of residues is an intrinsic
component of the tillage system. Another more direct example would be where a strongly deep rooting crop is chosen to break up a deep compacted layer in a reduced tillage system rather than to use a deep tillage operation. Of key importance is the compatibility of all components of the crop production system, including the crop and the tillage system used.

Some groups of crops require specific soil conditions to be provided by the tillage system, for example:
- Tuber and root crops: A deep, loose root zone is required, with some crops also requiring ridges or beds to facilitate harvesting.
- Small seeded crops requiring precision planting: A uniform finely granulated seedbed is required.
- Some short statured crops: A trash free surface, where trash would interfere with the harvesting operations, e.g., cotton and some vegetables.

The main characteristics of the crop to be grown which affect tillage selection include; planting requirements, germination, emergence and seedling development characteristics, rooting depth, and fertilizer and harvesting requirements, and these are outlined below.

2.4.1.1. Planting Requirements

The main areas in which the planting requirements have some affect on the choice of tillage system are seed size, equipment to be used for planting, and the planting date, rate and depth.

A. Seed Size and Seed-Soil Contact

During germination seeds imbibe the water from their immediate surroundings and it is important that there is good contact between the seed and the surrounding soil to facilitate this. This is particularly true in arid areas where the water may be limiting and is strongly attracted to the soil particles during dry periods. The soil underneath the seed should ideally be connected by capillary contact to moist soil. If the seed is planted mechanically, then the optimum conditions for seed-soil contact are achieved when the planter is designed to pack the soil below the seed level, press the seeds into the compacted soil, and cover the seeds with loose soil. This can also be achieved by hand planting, by gently pressing the seed into the hole with the foot prior to covering it. Coverage of the seed with soil reduces evaporation from the seed zone and also protects the seed from bird and insect damage.

Small seeds require a finer tilth in the seed zone than larger seeds to achieve good seed-soil contact. The size of the soil aggregates in the seed zone should generally be 1 to 5 mm in size with the smaller seeds requiring aggregate sizes at the bottom of this range. This requirement determines the type and number of secondary tillage operations required to achieve this tilth. The whole surface area of the field is generally tilled to the required tilth. For row crops this is not required as it is only the soil in the row that needs to be at the correct tilth. Furthermore it may be desirable for the inter-row tilth to be much rougher to promote water infiltration and reduce erosion, etc. However, this generally requires specialised equipment that can perform one or more tillage operations at the same time as planting and is not frequently used. A simple system based on this concept is wheel track planting, in which the planters are lined up behind the tyres of a tractor, and sometimes an additional tyre in the centre to provide closer row spacing, with the weight of the tires crushing the clods and producing the seedbed, while leaving a cloddy surface in the inter-rows. However, this system can result in the seed being planted into compacted areas, especially as planting is normally carried out when the field is fairly moist.

Good seed-soil contact is especially important in well aggregated and coarse soils. In sandy soils seeds hydrate more rapidly, and dry the surrounding soil more quickly, than when
planted in soils with a high clay content, (Godwin 1990). However, most problems with poor seed-soil contact occur on dry clay soils that become cloddy when tilled or planted. On these soils the clods must be broken down into soil aggregates of 1 to 5 mm diameter by secondary tillage or weathering to achieve good contact. Seedbeds on clay soils in dry regions should generally be prepared well before planting so weathering can break down clods. Only tillage necessary to control weeds should be performed immediately before, or in conjunction with, planting. Contact herbicides can also be used in lieu of tillage to kill weeds prior to planting.

Poor seed-soil contact can also occur when planting in wet clay soils, as the soils may adhere to the openers and result in a cloddy uneven seedbed. The wet clay soils can also block the seed outlets and clay soil are also highly prone to compaction when wet. Under these conditions planting should be delayed or if it is a chronic problem then the fields should be better drained.

For mechanised planting, the availability of implements that can plant through stubble largely determines whether conservation tillage systems with the retention of crop residues on the surface are viable options. Although most tractor drawn planters can cope with low quantities of residues on the surface, specialised planters are required for planting into heavy crop residues. Available animal drawn planters can generally not plant through crop residues. However, due to the generally uneconomic cost of using relatively expensive planters on small plots, most small farmers plant by hand, using planting sticks, hoes or dropping the seeds behind ploughs. For those farmers who plant by hand the retention of crop residues on the surface need not conflict with their planting system.

Planters designed to plant through surface residue usually use coulters to cut through the residues, but if the residues are wet, or the soil is soft, residues may be pushed into the soil instead of cut. Seed dropped onto these residues will have poor seed-soil contact. However, when residues are left on the surface the seed zone will generally be wetter because of improved infiltration and reduced evaporation and this may compensate for the poor seed-soil contact. Poor contact also occurs when planting in firm soil without enough loose soil to cover the seed, or when the over-firm soil does not allow the press wheel to close the slot around the seed.

B. Planting Date

The geographic location and climate determines the maximum length of the growing season in any particular area. Tillage systems cannot usually extend this season but ones can be selected which will make maximum use of the full season. Most countries have seed breeding programmes to provide cultivars suited to their various agro-ecological regions, and it is important that the appropriate cultivars are promoted by the extension staff.

The start and end of the growing season is controlled by either precipitation or temperature. Tillage systems can be used to conserve water during the rainy season and to maintain the moisture content of the soil at the end of the season at levels that allow growth for a short period after the rains end. As discussed in Section 2.1.2.4, they can also be used to carry over moisture from the previous rainy season so that at the start of the next season the topsoil is not totally dry, which would result in planting having to be delayed until sufficient precipitation has occurred to fully moisten the topsoil. In regions where autumn ploughing is not carried out, where the soils become very hard during the dry season, and where animal draught is used, planting is frequently delayed by several weeks, as the primary and secondary tillage operations are only carried out after the start of the rains. As discussed in Section 2.3.2.2, in regions where the crop yield is limited by the length of the season then a delay in planting can result in yield reductions of 5 to 10% per weeks delay.

Tillage systems can also be used to affect soil temperatures. The rate of hydration of the seed is controlled primarily by the water content of the surrounding soil and by the
temperature of the seed zone. Cold temperatures can be the limiting factor in moist soils. Table 3.1 (Godwin 1990, p 73, table 3.1) gives the temperature range for the germination of some common seeds. As a bare soil warms and cools faster than a mulch covered soil, and as a dry soil warms and cools faster than a wet soil, the use of appropriate tillage systems can be used to speed up the warming of soils as discussed in Section 2.3.1.2.

The basic principles used in the selection of planting dates are given in FAO publication No. 33 together with examples. One example given by Godwin (1990) is given here to outline the principles involved. Sorghum should be seeded so that adequate water is available during the vegetative stage to produce vigorous plants with high yield potential. Ample water should also be available to the plant during flowering, which is a critical stage when water and temperature stress should be avoided. In the Southern Great Plains, USA, for example, dryland sorghum can be planted as early as May 1st to 15th, but planting at this time results in flowering in July when temperatures are highest. By delaying the planting until June 10th to 20th, flowering occurs in mid- to late August when temperatures are lower, thus reducing drought stress and increasing grain yield. Other factors, such as the onset of insect or disease problems should also be considered. Early planting of sorghum in Texas, USA, avoids midge (Cononarinia sorghicola Coq.) infestations. In India, late planted rainy season sorghum may be destroyed by shoot-fly (Akterigona angustatus).

C. Planting Rate

The calculation of the desirable planting rate for a specific crop or cultivar is based on the expected germination rate and seedling emergence, planting method, available water supply and the plant's growth habit.

The germination rate is normally given by the seed vendor, but if not then this can be estimated by germinating a representative sample on moist paper, cloth or soil, under controlled conditions. Germination rates are usually of the order of 85% to 95%.

The seedling emergence percentages are more difficult to establish because they depend on a number of factors. Emergence in crusting soils will depend heavily on the efficacy of the crusting control measures used. If well adjusted precision planting equipment is to be used then a higher percentage emergence can be expected than if crude systems such as broadcasting are to be used, because the planting depth and seed-soil contact will be much more variable with broadcast seed. Lack of emergence due to pest damage also needs to be taken into account. If viable seed is accurately planted in well prepared seedbeds then under good conditions high emergence percentages of roughly 10% to 15% lower than the laboratory tested germination rates can be expected.

Extension or research services generally provide farmers with the planting rates to use for specific seeds and soil types and climatic zones. They should calculate the germination and emergence percentages on local lands, belonging to typically good and poor farmers, so that realistic values for these can be used when calculating the planting rate that farmers should use.

Planting rates should also be adjusted to the available water supply. Water availability may be judged from known irrigation reserves, or based on the anticipated annual rainfall that frequently follows fairly specific cycles of dry or wet years. If a water deficit is anticipated then planting rates should be lower than if an adequate amount of water is expected to be available.

A plant's growth habit also strongly influences the optimum planting rate. Plants with a branching growth habit or large leaves, such as many broad-leaf species, normally are planted at lower rates than those with little or no branching, such as maize or cereal crops. Wheat, oats and barley may tiller profusely if planted at low rates and thereby compensate for low populations if conditions are favourable.
D. Planting Depth

Two main factors determine the optimum planting depth for seeds. These are the ability of the growing shoot to push its way through the soil above the seed, and the requirement that once germination starts the seed should be surrounded by moist soil and that the soil should remain moist until the seedling is established. Generally the planting depth of a seed is ten times its diameter, as shown in Figure ___ (AGRITEX AP3 p 4.5, fig. 4.2.). However, this depth needs to be adjusted to allow for soil moisture conditions and expected rainfall patterns. If the crop is planted after the first rains it may be desirable to soak the seed for 12 to 18 hours before planting in order to reduce the germination time, which can be critical if the rains are not regular at planting time. However, soaking can reduce the effect of seed dressing and also makes the seed more vulnerable to damage by the mechanical metering devices in planters.

Tillage operations need to be selected that will prepare the seedbed at least 50 mm deeper than the seed is to be placed and should not be less than the depth to which the fertilizer is to be placed. This ensures that the conditions are optimal for the growth of the primary root, as well as ensures that soil conditions are optimal for the use of planting and fertilizing machinery, taking into account the variability to be expected in the control of depth of any tillage operation. This generally applies unless specialised zero-till planting and fertilizing equipment is to be used, and the soil conditions are such that the soil is suitable for germination, emergence and seedling growth without additional tillage operations being carried out.

The ability of the growing shoot to push its way through the soil from depth is dependent on the amount of food reserves in the seed and hence is generally dependent on the size of the seed. For this reason the smaller the seed the closer it is normally planted to the surface. Seedling vigour may be reduced by deep planting, because of the excessive use of the stored food reserves prior to emergence, and as a general rule seeds should be planted as shallow as conditions permit. However some crops have special requirements, for example wheat can be planted too shallow for proper crown root set. Care should also be taken that seeds are not planted so close to the surface that the developing root will force the seed out of the ground, or that the seed will be vulnerable to destruction on the surface by birds, etc.

The second main requirement for the planting depth of seeds is that the soil surrounding them should remain moist from the time that they start to germinate until the seedling is established. If germination is initiated and the soil dries out before the seedling is established then the seedling will die. In areas of low rainfall the planting depth should be deeper than in more humid areas, because the soil dries from the top downwards and a shallow seed zone will dry more rapidly than a deeper one. When a high probability exists that adequate rainfall will occur after planting then it may be desirable to plant at a shallow depth in soils prone to crusting so that the seedlings emerge before a dense crust develops. Shallow planting can also be used when the soil surface is protected by crop residues or mulches, as these slow drying and prolong the desirable moisture conditions for favourable germination and emergence.

Dry planting, i.e. planting into soil that is too dry to initiate germination, is practised in some regions to ensure that maximum use is made of the growing season. When using this system it is important the seed is sown deeply enough so that any small intermittent showers occurring before the start of the main rains do not initiate germination. In the semi-and tropics of India, where a monsoon rainfall pattern exists, sorghum is dry planted at a depth of 70 to 100 mm at the end of the dry period. This advances the growing season, allows more efficient use of monsoon rainfall, and avoids late season insect problems that sometimes occur.

2.4.1.2. Germination, Emergence and Seedling and Crop Development
Tillage affects germination, emergence and seedling development primarily by its affect on moisture, soil structure and fertility. Seed germination starts with the seed imbibing water, which causes it to swell to approximately twice its air-dry volume and culminates with the protrusion of the primary root, or radicle, from the seed coat. All the initial cell building material and energy required for growth, with the exception of water, is contained within the seed. Only after emergence can sunlight be used through the process of photosynthesis in the chloroplast cells to provide these requirements. The rate of hydration is controlled primarily by the water content of the surrounding soil and by the temperature conditions in the seed zone. If the soil water content in the seed zone is below permanent wilting point the seed may not germinate, or may germinate but not emerge. However, some crops particularly suited to dryland agriculture can germinate in rather dry soil, e.g. sorghum and cotton. If the soil water content is above field capacity then aeration may be too low for germination. Adequate aeration is required to allow the biological processes within the seed to proceed at an optimum rate. Where excess water is a problem drainage can be provided through either surface or subsurface drains.

Several factors can lead to poor emergence despite the use of viable seed. For good emergence the most important factor is the need for plant available water immediately below the seed zone. The water is initially used for root growth and only after their establishment is the water used for shoot growth and emergence through the soil surface. The next most important factor for emergence is a sufficiently low soil strength so that it does not impede the penetration of the radicle and shoot. Compacted layers either below or above the seed can affect growth. A compacted zone immediately below the seed will limit the elongation of the crucial early roots, and water uptake for shoot elongation will be slowed. The formation of a crust, or compacted layer, above the seed can be strong enough to prevent emergence. Soil crusting causes the emerging plant to crumple or to turn sideways, and to lose the special geometry that facilitates movement of the shoot through the soil. As discussed previously in Section 2.1.2.7 soil crusts are caused by raindrop impact on the soil surface. The most effective means of controlling crusting is the use of crop residues. Crop residues not only protect the surface, but by reducing surface evaporation and increasing the surface moisture content they also weaken the strength of any crusts that are formed. Crusts in clean tillage systems can also be broken mechanically by the use of rotary hoes (rolling tines) operating at a depth and speed that breaks the crust but does not injure the underlying seedlings.

A means of determining the adequacy of seedbeds for germination and emergence is given in Godwin (1990).

The effects of tillage on root development and function are by far the most important in the role of tillage in seedling development. These reductions in root growth and function cause plant stress which results in decreases in shoot development and expansion. Generally, poorly selected tillage operations can result in the following:

- Reduced availability of soil water and minerals.
- A decrease in root surface area available for the absorption of soil water and minerals.
- Decreased soil temperatures during early growth which can cause a reduction in both root growth and root absorbing ability.

The direct effects of tillage on shoot development are less pronounced and occur mainly through the shading of crop plants by stubble or weeds. Shading results in reduced light intensity and hence less photosynthesis and less growth.

Different crop species have different maximum rooting depths for the mature plant and this is an important consideration when checking for compacted and impermeable layers prior to tillage, and hence in determining the desirable primary tillage depth and possibly the use of subsoilers to break up hard pans. Poorly selected tillage operations can result in the reduced availability of soil water and nutrients as well as a decreased root surface area to absorb these
in mature plants as well as seedlings. Ensuring that the crop roots can grow to their maximum depth and that the water and nutrients can infiltrate to this depth, ensures the maximum availability of water and nutrients and the maximum ability of the plant to absorb these. As noted in Section 2.1.2.7., some crops with strong root penetration characteristics can sometimes be used in crop rotations to break up compacted layers, without the energy expenditure required for the implementation of subsoiling operations.

Tillage operations following seedling establishment are not normally carried out for small grains because the narrow row spacings preclude tillage. Control of weeds is normally by the use of herbicides and this will be discussed later. In wide spaced rowcrops such as maize and sorghum the role of tillage following seedling establishment is to promote soil and water conservation, and the maintenance of soil organic matter and nutritional levels. With the exception of zero-till systems this involves maintaining the soil surface in a non-erodible condition; maximising water infiltration in arid areas; top dressing with fertilizers; and controlling weeds to reduce the competition for water, and to limit the amount of carry over of weeds into the next season through either vegetative production or seeding. These measures are primarily required during the early stages of crop development prior to the establishment of a full canopy by the crop, which will protect the soil and promote water conservation. Care should be taken to limit tillage to essential operations so as not to speed up the decomposition of soil organic matter or to waste energy resources. Care should also be taken to avoid initiating compaction problems.

2.4.1.3. Nutrient and Fertilizer Requirements

Nutrient and fertilizer requirements depend primarily on crop type, on soil texture and soil condition. A detailed coverage of this important subject is beyond the scope of this publication and only those aspects directly related to tillage will be covered. Several FAO publications cover this subject in detail. As most publications discuss nutrient requirements and their application in the context of conventional, clean tillage, emphasis will be given here to their application to conservation tillage systems. Gait (1989) covers the nutrient and fertilizer requirements of conservation tillage in Zimbabwe for large-scale commercial farmers, and this publication is also directly relevant to small and medium-scale farmers.

There are 16 essential elements necessary for normal crop growth, and if any of these are missing growth will be retarded or the crop may die.

- Three essential nutrients—carbon (C), hydrogen (H) and oxygen (O₂), are taken up from atmospheric carbon dioxide and water.
- The other 13 nutrients are taken up from the soil and are usually grouped as primary nutrients, secondary nutrients and micronutrients.
  - Primary nutrients: Nitrogen (N), phosphorus (P) and potassium (K), are commonly found in blended fertilizers such as 10-10-10, or equivalent grades. Primary nutrients are utilised in the largest amounts by crops, and therefore, are applied at higher rates than secondary nutrients and micronutrients.
  - Secondary nutrients: Calcium (Ca), magnesium (Mg) and sulphur (S), are required in smaller amounts than the primary nutrients. The major source for supplementing the soil with calcium and magnesium is dolomitic lime (aglime), although these nutrients are also available from a variety of fertilizer sources. Sulphur is available in fertilizers such as potassium and magnesium sulphate, gypsum (calcium sulphate) and elemental sulphur.
  - Micronutrients: Iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B) and molybdenum (Mo), are required in even smaller amounts than secondary nutrients. They are available in manganese, zinc and copper sulphates, oxides, oxy-sulphates and chelates, as well as in boric acid and ammonium molybdate.

Fertilizers are divided into two main categories, namely, organic fertilizers, which
provide nutrients and organic matter, and inorganic fertilizers, which provide nutrients. Organic fertilizers are generally in the form of dry farmyard manure or compost, wet slurry, or green manures. Inorganic fertilizers may be in the form of liquids, granules, or powders. Both affect soil pH, with organic fertilizers providing more of a buffering action, and inorganic fertilizers, and especially nitrogenous fertilizers, capable of substantially reducing pH over a period of time.

Many small-scale farmers are resource-poor and either do not use artificial fertilizers or use them very sparingly. This aspect is discussed further at the end of this section. For these farmers the maintenance of an acceptable nutrient status of their soils, through the maintenance of soil organic matter by using conservation tillage systems is probably even more important than for richer farmers. However, many of these farmers do not, or cannot, use conservation tillage systems because of the increased weed, pest and disease problems associated with these systems. Particularly for these farmers the use of animal manures is a very important means of maintaining nutrient and soil organic matter levels.

The addition of adequate quantities of manure to the soil raises the pH of acid soil, decreases nematode damage, and by increasing the soil organic matter level improves soil structure, thereby increasing infiltration and reducing soil erosion and increasing the moisture and nutrient holding properties of the soil. Good quality manure also adds essential nutrients to the soil. There is a long tradition of using animal manures to maintain nutrient levels and a fair amount of research has been carried out on the best means of application of these manures. Grant (1981) recommends that manures should be banded in or near the planting rows, so as to concentrate them in the root zone of the growing plant, and that they should be placed roughly 5 cm below the surface to minimise their loss from any possible soil erosion. This can be done using an animal drawn plough to open and close the furrow. Otherwise the manure can be placed directly in deeper than usual hand dug planting holes and mixed with the soil, with the seed placed above. Spreading the manure on the soil prior to ploughing is the usual method of application, but this generally spreads the very limited amount of manure that is usually available too thinly over the field. General spreading of manure is however acceptable when the land is being ploughed prior to putting it under some form of reduced tillage system such as reduced-till tied-ridging.

Manure is at its most effective when it is mature and thoroughly mixed into the soil. Manure should be dug out from the cattle pens shortly before it is to be used. If it is to be incorporated through ploughing then it should only be spread out onto the field immediately before ploughing, to minimise the loss of nitrogenous matter to the atmosphere through oxidation. The composting of crop residues, weeds and other vegetable matter, such as field grasses and tree leaves, and especially those from the leguminacea family, and kitchen wastes is another important means of maintaining nutrient levels. These can be applied in the same manner as manure.

Another important approach is multiple cropping and especially strip cropping with crop rotations, with the use of rows of legume crops to intersperse the other crops. This system was frequently used prior to the introduction of monocropping to facilitate mechanisation and is still commonly used in West Africa. As described in Section 2.2.1.3 this system has been found to be very efficient at minimising soil and water losses, and in minimising the amount of additional fertilizer that is required to achieve acceptable yields. Crop rotations and multiple cropping systems are discussed in Section 3.2.2. The alternative approaches for maintaining soil fertility for the resource-poor farmers need to be researched and extended far more fully than they have been to date.

The main means by which nutrients and fertilizers are lost and the ways in which these losses can be controlled are listed below:
- Oxidation of some components, especially nitrogenous components, and their loss to the atmosphere: The main means of controlling this loss is to directly place the fertilizer
within the soil, or to leave it on the surface prior to incorporation for as short a time as possible.

- Soil erosion: As described previously in the section on soil erosion the loss of nutrients during soil erosion is twice the amount expected considering the weight of loss of soil. The means of control of this loss is to reduce soil erosion losses.

- Leaching: Nutrient and fertilizer particles are either held in the soil by clay particles and soil organic matter or are unattached. When water drains through the soil it readily dissolves and carries those unattached particles with it. These nutrients are then carried by the percolating water into the ground water or to soil layers well below the maximum rooting depth of the crop. The main means of control of leaching is to increase the soil organic matter levels so as to hold the nutrients in the soil.

In sandy soils with low clay contents and low soil organic matter contents, very few of the fertilizer particles are held to the soil and so are very vulnerable to leaching from water percolating through them. In these soils it is particularly important to increase soil organic matter so as to reduce the leaching of fertilizers. In heavy clay soils the fertilizers can be so fixated, i.e. held tightly, to the clay particles that a proportion of them are not available to the plants. When this occurs additional fertilizer has to be applied to fill these fixation sites so that the rest is available to the plants.

Tillage systems affect the loss of fertilizers and nutrients primarily through their effect on soil loss due to erosion, and due to their effect on the soil organic matter levels. These subjects have been discussed in Sections 2.2. and 2.1.3 respectively. One tillage system that should have a significant effect on reducing losses both through reducing erosion and reducing leaching is the tied-ridging system. Erosion losses with this system are minimal when it is correctly laid out. With regard to leaching, following excess rain the main path of water draining through the soil is from the furrow downwards and, as the manures and fertilizers are placed in the centre of the ridge and roughly halfway between the top of the ridge and the furrow, there should be very little leaching of these nutrients. However, apparently no tests have been conducted to validate this, which is surprising seeing that the leaching of fertilizers is a serious and costly problem, particularly on well drained sandy soils.

Good soil sampling techniques and facilities for the analysis of soil samples, to determine nutrient requirements, help tremendously in the efficient use of nutrient and fertilizers for known crops. However, in many countries these facilities are not available for the small and medium-scale farmers. In these cases the standard recommended levels are generally used, and any additional nutrient requirements have to be inferred from the condition of previous and current crops and the condition of the soil. Because of the limited mixing of the soil in conservation systems, and especially zero-till, soil sampling can present problems. This is particularly true where fertilizers have been banded next to the planting line in previous years. Nutrients from banded fertilizers will be gradually distributed throughout the topsoil by decaying root and surface residues from previous crops. Fertilizer applications to subsequent crops should be based on the nutrient levels found in the inter-row. This is especially important if the crop following a row crop is to be broadcast. Generally, it is recommended that samples are taken from the inter-row area to a depth of 15 cm, after removing the surface trash and being careful not to scrape away any of the topsoil in the process.

When using conservation tillage systems it is generally important to maintain pH levels between 6 and 7.5. As discussed in Section 2.1.3.3 the soil microorganisms are most active at pH levels between 6.5 and 8.5, and crop growth is generally optimal for pH levels between 6 and 7.5. Prior to committing land to conservation tillage it is very important that the pH level is brought up to the correct levels so that lime, and possibly manure, can be fully incorporated into the soil to achieve the required level. If serious soil acidity problems do arise while conservation tillage is being used then it may be necessary to revert to a conventional system for a season so as to incorporate the lime.
As nitrogen fertilizer acidifies the soil and is generally placed at or near the soil surface, this is the most important zone for corrective liming. Under conservation tillage, lime should generally be applied in smaller quantities and more frequently than with conventional tillage systems. Furthermore, lime is best applied to the soil surface just before the rains or irrigation, as moisture is required to facilitate the reaction between the lime and the acid topsoil. It should not be applied to a dry soil as there will be no reaction with the soil until it becomes wet and high losses due to wind erosion can occur. If some form of tillage, such as rip on row, is used with the conservation tillage system, then it would be an advantage to apply lime prior to this operation to facilitate some incorporation with the soil.

Some fertilizers are easily translocated through the soil by infiltrating water and so their depth of placement in the soil is not critical. However, others are not easily distributed by infiltrating water and it important that they are placed at a depth where the main feeding roots of the specific crop occur. Furthermore some fertilizers can be placed on the soil surface whereas others lose important constituents to the atmosphere unless they are covered.

Under conservation tillage there is a build up of organic matter at the soil surface. As Gait (1989) points out soil analysis will tend to give misleading figures regarding the after-incubation nitrogen figures of the soil, since it assumes that organic matter will be broken down during the season, releasing nitrogen. Under conservation tillage only a small proportion of organic matter is broken down and very little extra nitrogen is released. Hence higher levels of nitrogen fertilizer are required than is the case for conventional tillage. Furthermore, as soil structure under conservation tillage improves so the yield potential will increase, and the nitrogen fertilizer requirement will increase if these yields are to be realised.

Nitrogen based fertilizers in strong concentrations can burn the seed and radicle if put in contact with them. Numerous trials have been conducted on the optimum placement of fertilizers in relation to seeds and these vary between species. However, a general guideline for most crops when fertilizing at the same time as seeding is to lay one band of fertilizer 5 cm to the side and 5 cm below the seed. This avoids direct contact between the fertilizer and the seed as well as the sensitive radicle. Feeder roots will rapidly grow towards the fertilizer band to extract the required nutrients. As the fertilizer is placed at least 8 to 10 cm below the soil surface its loss due to any soil erosion is minimised and losses to the atmosphere of nitrogen based fertilizers are also minimised. Another advantage of the deep placement of fertilizers in bands is that it encourages the crop to root more deeply and provides a supply of nutrients where available moisture is likely to be for longer periods. For closely spaced small grains one band can be placed between two rows.

When planting and fertilizing by hand the above dimensions can also be used. For example, if planting to 5 cm depth, a long hole 10 cm deep can be scooped out using a hoe, the fertilizer placed in one end of this and covered by 5 cm of soil scooped in using the foot, and the seed then planted on the other side of the hole to the fertilizer and covered. Calibration details of manual and machine operated fertilizing systems are given in detail in Section 5 together with detail of the on-farm modifications that can be made to planting and fertilizing equipment for use with crop residue tillage systems.

Gait (1989) lists the following long-term trends of conservation tillage with regard to nutrient levels:

- There will be immediate benefits in terms of reduced soil, water and nutrient run off. Full benefits in relation to the supply of nutrients to the crop and better yields are unlikely to be experienced until at least the fourth or fifth year.
- Fertilizer nutrients will tend to be concentrated in the top few centimetres of the soil, resulting in a marked difference in the nutrient levels and availability between the surface and lower layers. In well managed lands the nutrients at lower levels will tend to remain constant.
- There will be an increase in organic matter in the top few centimetres of topsoil,
increasing the cation exchange capacity of the soil. This will result in the topsoil becoming more fertile and better able to hold and provide nutrients to the crop.

- The residue layer on the surface will reduce the tendency for the soil surface to dry out by evaporation. Feeder root growth of the majority of crops will be shallower and sometimes right at the soil surface. The crop will make better use of the now highly fertile topsoil.
- The development and multiplication of beneficial soil fauna such as earthworms will help to cycle and distribute nutrients throughout the profile. This, however, is a long-term effect and the extent and resultant commercial benefit have yet to be ascertained.

The cost of artificial fertilizers is high and many resource-poor farmers either do not use them or use much less than the recommended quantities. It is very important that the agricultural extension personnel appreciate that resource-rich and resource-poor farmers use different strategies for the use of their resources, including the use of fertilizers, and that these different strategies are highly appropriate to their different situations. For example, many farmers in arid areas do not follow the standard recommendations of applying fertilizer with their seed during dry planting and will wait for the onset of reliable rains before applying it. This low input farming strategy is characterised by low total fertilizer application rates as well as by the fragmentary application of the fertilizer depending on the character of the rainfall patterns. In areas where there is a likelihood of a frequent total crop failure, say two years out of five, this strategy of conserving expensive fertilizer may make good financial sense for a resource-poor farmer, even though it leads to reduced yields in those years when rains are adequate and crops are harvested. Mackenzie (1987) showed that high fertilizer applications gave the highest potential profit in good seasons but also the highest potential loss in poor seasons. Grant (1981) also showed that when yield is limited by moisture stress it is generally uneconomic to apply large amounts of fertilizer. In areas where there is a high probability of a poor season occurring resource-poor farmers therefore opt for a low input farming strategy. This aspect will be discussed further in Section 2.5.

2.4.1.4. **Harvesting Requirements**

The specific harvesting requirements of some crops affect the choice of tillage systems. For example, the harvesting of some tuber and root crops, e.g. potatoes, is facilitated if these crops are grown on ridges or in beds. This also applies to a crop such as groundnuts. The design of these beds or ridges must be such that they allow easy access for the implements that will be used to lift the crop.

Some short statured crops, such as cotton when machine picked, also limit the choice of tillage system. Where the quality of the picked product is very important and where the stature of the crop is short, then the harvesting machinery is likely to pick up any trash on the surface and this may reduce the quality of the harvested product. This in turn excludes the selection of conservation tillage systems with the retention of crop residues from the previous crops. Harvesting of some short statured crops can also be improved by planting them on ridges, and if these ridges are constructed on slight gradients then they can be used to control erosion as no residues are being used to do this.

2.4.2. **Weed Control**

Weeds compete with a growing crop for water, nutrients and sunlight. Good weed control is essential in order to achieve the potential crop yields available in a particular agro-ecological area and this is particularly true of conservation tillage systems. A detailed coverage of this important subject is beyond the cope of this publication and only those aspects directly related to tillage will be covered. Several FAO publications cover this subject in detail. McConaghy (1989) covers weed control in conservation tillage systems in Zimbabwe for large-
scale commercial farmers, and this publication is also relevant to small and medium-scale farmers who have access to herbicides.

Good weed control is particularly important for efficient crop production in the arid and semi-arid areas, because weeds compete for water, which is one of the main limiting factors to crop growth in these areas. Moody (1974), demonstrated that crops differ in their susceptibility to weeds and the periods over which they are most susceptible, and some examples of these given by Unger (1984) are repeated below:

- Maize yields on plants kept weeded for the first 30 days after planting were only 5% lower than on plots kept weeded for the entire growing season. Similar results were obtained with soybeans and cowpeas, but yams had to be kept weeded for 3 months to hold yield losses to 5%. Although the emergence of weeds after these periods would only have a minor effect on yields, they could harbour pests, cause harvesting problems and if then seeded could result in a carry over of weeds to future cropping seasons.

- Uncontrolled weeds in maize for the first 12, 20 and 30 days after seeding decreased yields by 3, 12 and 22%, respectively. Cowpeas showed a yield decrease of 11% when weeded once at three weeks after emergence, and negligible losses if the crop was weeded at one and four weeks after emergence. Soybeans showed a yield decrease of 10% when weeds were allowed to grow in the crop for ten days and a further decrease of 10% when the weeds were not controlled for another ten days.

- Delayed weeding due to the slowness of hand labour can decrease yields of maize and soybeans by 40 to 50% on the area where weeds were controlled the latest. The example assumed that a farmer with three hectares of land to hoe started at 20 days, and 5 days was required to hoe each hectare.

- Weeds are less competitive when they emerge in a well developed crop with an extensive root system and enough leaf canopies to shade the soil and so restrict weed growth. However, certain weeds grow so rapidly and are so competitive that late weeding may be required in some crops.

The above examples demonstrate the importance of timely weed control and how large the yield losses can be when this is not done. Generally, crops are most susceptible to competition from weeds during their first month of growth and prior to the development of an extensive root system and leaf canopy. However, because of the different responses of the same crop grown under different conditions, generalised recommendations cannot be given which are applicable for all situations. For example, different crop cultivars, weed species, level of weed infestation, soil types, water limitations, etc., would all affect the above figures.

Weeds are easiest to destroy shortly after they have emerged. Once they have developed a dense root system they are difficult to eradicate using either tillage operations or herbicides. The timeliness of weed control operations is therefore extremely important. To achieve this any established or emerging weeds should be eradicated immediately prior to or during planting and weeds should ideally be eradicated before they reach 5 cm in height, especially during the first month of crop growth.

A very important approach to the efficient control of weeds is to prevent them seeding and so carrying over the problem to later years. For this reason the control of late weeds in the previous crop is very important, even if their presence will not have a significant effect on the yield of that crop.

The tillage operations used to destroy small weeds are usually harrowing or hoeing. These operations destroy weeds by either cutting the growing shoot off just below the surface, burying the plant, or the whole plant is in effect pulled out and allowed to dry on the surface. However, different weed species often require particular treatment. For those species that multiply largely through vegetative growth, e.g. grasses, tillage operations that do not kill the plant can result in increased propagation of the weeds. For serious weed infestation problems
complete inversion of the soil to bury the weeds using the mouldboard plough is often the best means of destroying them.

In conventional tillage systems the use of herbicides has had a major effect on increasing yields, both by improving the proportion of weeds destroyed during the operation and by improving the timeliness of the operations. The use of herbicides can also reduce machinery, energy and labour costs. In small-scale farming, without access to draught power, Zinyemba (1988) showed that the use of herbicides with knapsack applicators required only 1 labour day/ha/season as compared to 40 labour days/ha/season for hand weeding with hoes. Furthermore, when hired labour was used to carry out the hand weeding it cost three times the amount when compared to the use of herbicides.

However, small farmers in developing countries frequently do not have access to herbicides. This is usually because herbicides are expensive, as they are frequently imported rather than made within the country and their transportation to distant rural areas increases this cost. Government may also decide that scarce foreign exchange should not be used to purchase herbicides, except when they are to be used with foreign exchange earning crops. The cost of the applicators, and especially knapsack sprayers, is fairly reasonable when compared to the cost of other agricultural implements. However, for resource-poor farmers, and especially those farming in areas where the risk of a poor season is high, the capital cost of the equipment and the cost of the herbicides frequently means that their use is not cost effective. Good training in the safe use of herbicides is essential if herbicides are to be used. Although many of the most harmful chemicals used in herbicides have been banned, some chemicals are still used which can result in severe harm to the operators, the consumers and the environment. For these reasons it is essential that detailed information on the potential dangers of herbicides are available to extension workers, so that they can advise and train farmers in the safe use of the safest and most cost effective herbicides.

In conventional tillage systems weeds are controlled using tillage operations and cultivation practices, such as crop rotations, including fallow lands and herbicides. In conservation tillage systems on large-scale farms the control of weeds is primarily through the use of herbicides. Indeed many forms of conservation tillage systems were not possible before the development of modern herbicides. The use of crop rotations with conservation tillage systems is particularly important to assist in weed control. They are also an important means of pest and disease control and the maintenance of soil fertility. Conservation tillage systems can be used without the use of herbicides, when tillage operations are undertaken manually, using implements such as the hoe, and when cultivation practices such as crop rotations are used. Tillage operations to control weeds are not usually used in conservation systems for several reasons, namely:

- One of the objectives of conservation tillage systems is to disturb the soil as little as possible so as to conserve soil water, leave all crop residues on the surface and reduce energy expenditure.
- When the soil is disturbed dormant seeds are brought closer to the surface where they can germinate. By not inverting the soil, buried weeds remain dormant and the viability of the weed seeds left on the surface is reduced, particularly through exposure to sunlight.
- Few tillage implements for use with animal or motorised draught power have been developed for weeding in the presence of crop residues. This is partly due to the difficulties in meeting the operational requirements of the implement, and partly due to the lack of incentive due to the existence of modern herbicides.
- The use of modern herbicides is generally more cost effective than the use of tillage operations.

In conservation tillage systems the dependency on herbicides is much greater than in conventional tillage systems and their performance is more critical. Conservation tillage systems may restrict the use of some herbicides and eliminate the use of others that are
commonly used in conventional tillage practices. For example, herbicides that must be incorporated into the soil cannot be used effectively in many conservation tillage systems and especially in zero-till. Godwin (1990) lists the general requirements that herbicides should meet to perform satisfactorily with conservation tillage systems, and these are given below:

- Control vegetation present on the site.
- Prevent growth of weeds from seed that germinates after the herbicide application.
- Not injure the crop.
- Not injure subsequent crops due to residues remaining in the soil.

The importance of these requirements will vary depending on the geographical location, the soils, crop grown, and conservation tillage system used.

In order to meet the above requirements combinations of herbicides usually are necessary. In relation to the crop plants they can be applied under a pre-plant, pre-emergent or post-emergent basis. Two main categories of herbicides based on activity are defined below:

- Contact herbicides - destroy only the plant tissue in contact with the chemical. These are generally the fastest acting herbicides, but are less effective on perennial plants, which are able to regrow from rhizomes, roots or tubers.
- Systemic herbicides - are translocated through the plant, either from the leaves down to the roots, or from soil application up to the leaves. They are capable of controlling perennial plants.

Some general points can be made about the use of herbicides, however the details of their use are beyond the scope of this text. In order to improve the contact between the herbicide and its target a "wetter" is used with some herbicides. It is important not to mix contact and systemic herbicides in the tank because their respective actions are frequently antagonistic. There are large ranges of nozzle types suited to different applications and the various herbicides are required to be applied at different pressures and different concentrations.

Although most weeds, and especially broadleaved weeds, can be controlled by herbicides, some grass weeds growing in grain crops can not, as the crop is also susceptible to some of the herbicides used to control grasses, as the grain crops also belong to the grass family, the graminacea. In these cases some tillage may be essential. This aspect is also one of the main reasons why the use of crop rotations are important in the control of weeds, and especially the alternation of dicotyledons with monocotyledons. While a monocotyledon crop is being grown herbicides can most effectively be used against dicotyledon weeds. As this allows some build up of monocotyledon weeds, changing the crop to a dicotyledon the following year allows the carry over of the monocotyledon weeds from the previous year to be easily targeted.

One of the most important aspects of good herbicide use is good management knowledge and planning, and McConaghy (1989) emphasises the following points for farmers:

- Know the weed spectrum in the land, know the herbicides that are available, how and when best to use them and clearly understand their limitations. Always read the label.
- Know the characteristics of the different weed species. Some may germinate early in the season, some later, some germinate over a protracted period of the growing season, and some are annual and some perennial.
- Know the clay and silt content of the soils as this can affect choice and performance of some herbicides.
- Know what spray equipment will be required, what size nozzles will be needed and at what pressure they should operate to deliver what volume. Know in advance whether any surfactant or additive is needed, and if so, why. Where surfactants are advised they can increase the efficiency of herbicides for a small outlay.
- Design a weed plan for each land.
- Tackle major weed problems before embarking on a conservation tillage programme. If a conservation tillage programme is already underway and major weed problems occur it may be necessary to revert to a conventional tillage programme for a season to
control the weeds. Start weed control by controlling the late weeds in the previous crop.

- Ensure that the right equipment is available, is in good condition and that the operators are properly trained.

The application of herbicides is a specialised field and it is essential that extension staff are fully trained in the use of herbicides prior to the promotion of their use. This is essential both because of the safety of the farmers, the safety of the consumers, the protection of the environment, and because of the cost of use and misuse of herbicides.

2.4.3. **Pest Control**

The main animal groups that can become pests in agricultural production are insects and nematodes. Other groups such as birds and mammals can also become pests but are not affected by tillage and will not be considered here. Pests are basically animals that feed on agricultural crops, and occur in the wrong place at the wrong time and in sufficient numbers to cause damage above an acceptable level to the crop. Under different conditions the pest species may be innocuous or even beneficial. Almost every animal species has a number of natural predators, and under natural conditions, the predator-prey relationship is one of the factors that contributes towards the maintenance of stability of populations. The system of mono-cropping, which is used primarily to facilitate mechanisation, facilitates population explosions of pest species by providing an abundance of food of one type over a relatively short period of time and generally precludes the possibility of balance between predators and prey. However, a number of natural, and especially climatic, factors can also result in population explosions and collapses of a specific species. For example, a sequence of two or more low rainfall seasons favours most soil pests because, with heavy rainfall, many soil pests are drowned or forced to leave their burrows.

A detailed coverage of this important subject is beyond the scope of this publication and only those aspects directly related to tillage will be covered. Several FAO publications cover this subject in detail. Bissett (1989) covers pest control in conservation tillage systems in Zimbabwe for large-scale commercial farmers, and this publication is also relevant to small and medium-scale farmers.

Prior to the use of insecticides pest control was based on early ploughing, clean cultivation and crop rotations. These measures are still the main pest control measures used by many small-scale farmers, especially where the availability of pesticides is limited either because of the low resource base of the farmer or because of distribution problems. These pest control measures are described below:

- **Early ploughing:**
  
  Soil disturbance can kill pest larvae, pupae and adults either directly or indirectly, by burying them too deeply, destroying their burrows or bringing them to the surface, and so placing them in a physical environment in which they cannot survive or which otherwise increases their vulnerability to predation by other animals. Early rather than late ploughing is generally required so that soil clods can dry out and desiccate the insects, etc.

- **Clean cultivation:**
  
  Crop residues left on the surface both act as a medium for physically carrying over the eggs, larvae, pupae, or adults from one crop into the next crop, as well as providing shelter and a food source for those insects. When crop residues are ploughed in and fully covered using a mouldboard plough, then the insects living in them are usually destroyed. Partial incorporation of the residues results in a higher carry over of pests than full soil inversion and complete incorporation.

- **Crop rotations:**
  
  Different crops are generally prone to a particular range of pests that feed off
them or live in them. In serial mono-cropping the pests carried over from one crop to the next are exactly those pests to which the crop is most vulnerable. This annual carry over of pests allows the pest populations to build up rapidly in this system, both during the cropping system and from year to year. By carefully rotating the crops, so that the one crop following the other is not vulnerable to the same pests, the problem of carry over and the build up of pests is substantially reduced.

Unfortunately the first two pest control measures described above preclude the use of conservation tillage systems. The control of pests in conservation tillage systems is generally more of a problem than in conventional systems, because the pests are not destroyed by tillage operations and they can also be carried over to the following crop through the retention of crop residues on the surface. Because of this the use of crop rotations in conservation tillage systems is even more important as a means of controlling pests than it is in conventional tillage. Conservation tillage is also generally only viable when farmers have access to a certain minimum range of pesticides. For farmers with access to these pesticides the benefits of conservation tillage generally outweigh the potential for increased pest problems with this system. Because of the problem of pest species building up a resistance to certain pesticides the use of crop rotations is again very important, so that the same pest infestations are not occurring in successive years and so requiring the use of the same pesticides in successive years. However, the cost of pesticides and the danger of the use of many pesticides to the operators, the consumers and the environment is a very important consideration and this will be discussed at the end of this section.

In conservation tillage systems the retention of crop residues on the surface, coupled with a minimum amount of tillage, results in increased pest populations and especially of those pests living in the soil. They can, however, also result in an increase in the populations of natural predators. Most pest control measures, and especially those using pesticides, destroy both the pest species as well as their predators, which is inefficient and undesirable but frequently cannot be avoided. The careful and timely application of specific pesticides can sometimes be used to destroy the pest species but not the natural predators, and so both reduce the damage caused by the pests as well as reduce the cost of pesticide applications. This approach is part of the system of biological control, which can also involve the breeding of natural predators and their distribution into the crop at appropriate times. These natural predators are sometimes associated with specific plants and, if so, these can be grown around a field to build up the population of natural predators. The distribution of these predators into the field can also be assisted by reaping some of the host plants and distributing them in the crop, or as has been tested in the U.K., hovering the predators off the host plants and blowing them into the crop.

Regardless of the tillage system used the presence of pests in crops is inevitable. The objective of pest control is not to eradicate pests, as this is generally impossible, but to manage their numbers so as to keep them below the level at which economic damage occurs. This level is determined by the balance between the cost of pest damage and the cost of pest control. A higher level of pest management is required with conservation tillage than with other systems.

With the exception of the use of tillage operations and clean tillage systems to control pests the remainder of the pest control measures are the same for all tillage systems. Incorporation of insecticides is more of a problem with conservation tillage but new insecticides can be used as seed dressings, placed in the planting holes or banded in the planting slot in front of the press wheels and so incorporated into the soil without the requirement for heavy soil movement implements. The basic differences between pest management for conventional and conservation tillage systems are a greater need for the full implementation of pest scouting procedures and for crop rotations.
Some examples of pest control measures listed by Bissett (1989), which are primarily applicable to conservation tillage systems are given below to demonstrate some of the principles involved:

- **Maize stalkborer (Busseola fusca):**
  Deep ploughing and the destruction of maize stalks is the conventional means used to control the maize stalkborer. However from research carried out in Zimbabwe (Plant Protection Research Institute, Zimbabwe, Annual Report 1973/74), it was found that adequate control could be achieved by knocking all the maize plants over. This exposed the over-wintering caterpillars to direct sunlight and heat on the ground and increased predation by ants. Grazing alone was found to be inadequate unless all the stalks were knocked over early in the dry season.

- **Cutworms (Agrotis spp.):**
  All crops are at risk from cutworm attack particularly during germination. Cutworm larvae require green plant material on which to feed and irrespective of the tillage method, weedy lands will increase the potential of cutworm attack. Other than weed control methods cutworm control is essentially the same for both conventional and conservation tillage systems. The main control methods are listed below:
    o Control late weeds by directed post-emergent herbicides so crops finish up as weed free as possible. This will prevent cutworm populations becoming established and being carried over into the following crop.
    o Control subsequent post-harvest weed infestations with herbicides. If this is done a month or more before the next crop is planted any resident cutworm population feeding on these weeds will die of starvation. This will ensure that mature cutworms are not present when the next crop is in the susceptible germination stage.
    o Scout regularly during crop emergence. Early detection of infestations is important as control of the young leaf-feeding caterpillars is relatively easy compared with control of the older soil-inhabiting stages.

- **Nematodes (Meloidogyne spp., Pratylenchus spp., etc.)**
  A number of different genera and species of nematodes are pests of crops and they can severely depress yields. The main means of pest control are listed below:
    o Tillage: In conventional tillage systems ploughing out crop roots after harvest reduces nematode numbers by reducing their food supply and subjecting them to heat and drying.
    o Crop rotations: For each nematode pest there are crops which are poor hosts, i.e. they do not provide the food the nematodes require or they resist penetration by the nematodes, and hence the use of crop rotations is an important means of pest control. Although tillage reduces nematode numbers they increase rapidly when a susceptible crop such as tobacco is grown. Serial monoculture is an important cause of severe nematode infestation.
    o Pesticides: In conservation tillage systems pesticides can be incorporated into the soil by banding in front of the planting press wheels.

- **Nematode attack on crops is most important on sandy soils.** This is partly because of their poorer nutritional status and partly because nematodes can locate roots more easily due to the relative absence of fine clay particles which appear to restrict their movement. In conservation tillage systems the build up of humus in the soil profile may hamper the ability of nematodes to move and locate plants. Furthermore, there is also evidence that the increased humus content of soils reduces the severity of nematode injury to plants due to a build up of nematode trapping fungi.

A thorough knowledge of the potential pest species and their life cycles, together with thorough management and planning are essential for the efficient control of pests. One of the most important aspects of pest control is knowing at which stage in the crop growth the pest creates most damage, and at which stage in the pests life cycle the pest species is most vulnerable to destruction through the use of control methods. The basic management principles for good weed control, outlined at the end of the last section, is generally directly
convertible into those required for good pest control and will not be repeated here.

The application of pesticides is a specialised field and it is essential that extension staff are fully trained in the use of pesticides prior to the promotion of their use. Pesticides are generally more dangerous than herbicides to both humans and animals because they are targeted at animals and are usually not species or genera specific. Furthermore, any predator of that pest absorbs the pesticide used to control it and thus the dangerous chemical can work up the food chain to affect a large number of different animals. Residual pesticides on foodstuffs can also affect human consumers. Although several of the most harmful chemicals used in pesticides have been banned, some chemicals are still used which can result in severe harm to the farmers, the consumers and the environment. The toxicity of the pesticide to local non-target species and the life span of the pesticide are the main criteria of concern. For these reasons it is essential that detailed information on the potential dangers of pesticides are available to extension workers, so that they can advise and train farmers in the safe use of the safest and most cost effective pesticides.

2.4.4. Disease Control

Many diseases of crops are due to fungal infestations and the factors affecting the spread of diseases in plants are fairly similar to those affecting the spread of pests.

The effect of tillage on the spread of crop diseases is primarily limited to the retention of crop residues on the soil surface in conservation tillage systems. Any pathogens or spores on the fallen leaves, stems and roots left in the field can then reinfect the next crop. The main means of disease control are listed below:

- **Crop rotations:**
  Crop rotations can be used to ensure that the following crop is not susceptible to the same diseases as the previous crop. Some diseases only attack one genera and many diseases that attack monocotyledons do not attack dicotyledons and visa versa.

- **Control of disease vectors:**
  Some diseases are carried by insects and the control of these insects through pesticides, etc., can be used to control the spread of the disease.

- **Destruction of crop residues:**
  Destroying crop residues by deep ploughing or burning is an efficient means of control, although this method precludes continuous conservation tillage. However, conservation tillage systems can be used and every four years or so, when the disease level builds up to unacceptable levels, the residues can be deep ploughed. This system retains some of the benefits of conservation tillage while still controlling disease levels.

- **Maintenance of good control during the growing season:**
  The use of fungicides or other substances to control pathogens during the season ensures that the pathogen population at the end of the season is considerably reduced. As Cole (1989) points out, most pathogens have natural enemies and in conservation tillage these would have a chance to become established, and may reduce the pathogen population to levels at which economic damage to the following crop is unlikely to occur.

A thorough knowledge of the potential diseases and the way in which they are transmitted, together with thorough management and planning are essential for the efficient control diseases, and this is particularly true when conservation tillage systems are to be used. The basic management principles for good weed control, outlined at the end of the section on weeds, is generally directly convertible into those required for disease control and will not be repeated here.
2.4.5. The Effect of Tillage Operations, Depth of Tillage and Tillage Systems on Yield

The emphasis of this publication has not been on the yield response to a specific tillage operation. This is because the main yield response may be to any one of a number of the effects of the tillage operation on the soil in a particular field. Furthermore, a specific tillage operation in one climatic region on a particular soil type may have a totally different effect on yield when used in another climatic region, on the same or a different soil type, even though the short-term effects on the soil structure may be the same. For this reason the format of this publication has been to concentrate on the various soil properties, and how tillage can be used to alter them, as well as the effects that specific tillage systems have on other crop production components, such as weed infestation levels. Extension workers can then use this information to analyse problems related to tillage and to select appropriate tillage systems for a specific farm in their area. However, it must be emphasised that the effect of tillage on yield is of prime importance, as the main objective of the farmer is to maximise output over input. Yield responses to some tillage operations have been given in previous sections and in this section a few more will be given.

As Unger (1984) points out, many reports on trials of the effects of various tillage systems on the production of a particular crop do not evaluate the effect of the tillage system on the condition of the soil. This is a serious omission, as crops differ in their response to tillage induced differences such as soil water content, aeration, bulk density, soil strength, root zone depth, fertility and weed, pest and disease levels. Without measuring these parameters it is not possible to determine which factors are affecting plant growth. It is also not possible to infer the likely result of using the particular tillage system with a different crop, or in a different climatic region, etc. Unger (1984), quoted the example of a trial where two fibrous rooted grain crops, wheat and sorghum, responded primarily to the amount of water available for crop use, while their response to the soil physical conditions resulting from the tillage methods were marginal. In contrast, the response of a root crop such as sugar beet, was to tillage induced increases in water infiltration, as well as to decreases in bulk density and increases in the aeration in a dense clay loam soil.

In arid and semi-arid regions one of the main objectives of tillage is to increase soil water content, by increasing infiltration, increasing water holding capacity and reducing evaporation and evapotranspiration from weeds. As previously discussed in Section 2.1.2 several alternative tillage operations or systems can be used to achieve these objectives, depending on the characteristics of the climate, soil type, farmer's resources, etc. One trial together with some points summarised by Unger (1984) are repeated here. Hakimi and Kachru (1976) evaluated the effects of tillage type and depth on barley grain yields on a calcareous silt loam soil at Shiraz, Iran. A zero-till treatment was also included in the study and resulted in the lowest average yield, see Table ___ (@ Unger 1984, p 95, table 19). This low yield was attributed to weeds, but no herbicide had been applied. Furthermore, the plot was ploughed and then fallowed for one year before initiating the study. Highest yields were obtained from the field cultivator treatment, and were attributed to better water infiltration, lower soil bulk density, more extensive root growth and lower weed populations, as compared to the other treatments. The higher average yield with shallow tillage was attributed to better conservation of subsurface water, which contributed to more extensive root development than with other depths of cultivation.

Results somewhat different from the above were obtained by Papendick et al (1973), who obtained greater water conservation with 11 cm deep tillage than with 6 cm deep tillage. This was attributed to increased resistance to water flow from moist soil layers to the atmosphere and to increased thermal insulation of the moist soil by the dry soil mulch. The greater water content resulted in more rapid wheat seedling emergence and development. As reported by Smith (1988), following trials carried out in the 60's and 70's in Zimbabwe, the standard recommended depth of ploughing there is 20 to 25 cm.
As Unger (1984) points out the possible reasons for the different water conservation and yield responses to depth of tillage include soil differences, initial water contents, type and timing of tillage, environmental conditions and crops grown. The variable results emphasise that the prevailing local conditions must be carefully evaluated when planning tillage depths, because tillage deeper than needed for establishing a good seedbed will seldom be beneficial with respect to water conservation and crop yields. Where relatively deep tillage is used, i.e. below the seed zone, the initial operations should be the deepest, then subsequent tillage should be progressively shallower so that a firm, moist seedbed is available at crop planting time.

In addition to the effect of some specific tillage operations on yield, and how they are implemented, it is also important to consider the long and short-term effects of different tillage systems on yield. As discussed previously, the use of conventional tillage systems on virgin land can lead to a flush of nutrients as the soil organic matter decomposes, resulting in high initial yields. However, the use of conventional tillage systems in arid and semi-arid areas leads to a gradual decline in the organic matter levels of the soils. This leads to a decline in their structure and water infiltration and holding characteristics and nutritional levels. During precipitation deficient years, and without the use of additional fertilizers, yields under continuous conventional tillage can therefore be expected to decline. This is particularly true on shallow soils subject to erosion, unless ridging or other runoff reducing tillage operations are added to the conventional tillage system on the flat.

Elwell (1992) lists some of the results of trials on conventional and reduced tillage systems carried out in Zimbabwe on clay and sandy soils and these are given in Table ___ (Elwell 1992, p 32, table 4). Using this data together with a wider spread of the data from trials carried out in Zimbabwe from the late sixties to the mid eighties, on large and small-scale farms and primarily with maize and cotton, Smith (1988) generally found yields to be lower from reduced tillage systems than from conventional tillage systems. This was attributed to increased weed and pest levels and poorer rooting volumes. For reduced tillage systems in which substantial amounts of residues were left on the soil surface it was found that they gave higher yields in dry years, particularly on sloping lands and for low infiltration soils. However, they gave lower yields of maize in wet years, which was attributed to a loss of fertilizer through leaching and adverse changes in soil physical properties. In addition, Smith (1988) concluded that reduced tillage systems require lower levels of most inputs than conventional tillage, but also require higher levels of management to minimise adverse effects of pests, weeds and difficulties in handling surface residues.

As can be seen in Table ___ (Elwell 1992, p 32, table 4), although the yields of the conventional tillage systems were slightly higher than those of the reduced tillage systems, the percentage of organic matter and water stable aggregates were much higher in the reduced tillage systems after roughly 9 years. This demonstrates that the beneficial effects of the improved soil structure resulting from the reduced tillage systems were counterbalanced by the problems listed above. Vogel (1992) describes some on-station trials presently being carried out on sandy soils in Zimbabwe in which conventional tillage systems are being compared with conservation and reduced tillage systems. The systems are designed for use in the small-scale farming sector, and comparisons are being made in relation to soil and water loss and yield, and the long-term effects on soil condition. From the preliminary results to date it appears that the tied-ridging tillage system performed better than the others under high rainfall conditions both in terms of reduced soil loss and higher yield, but the draught and labour input requirements were high. Under arid climatic conditions the rip into mulch treatment produced the highest yields and gave very low soil loss rates, but the labour requirement for weed control was high. The rip without mulch treatment, where the rip line was in the old interrow line leaving the old plant base and roots intact, provide similar yields to the conventional tillage system in dry regions, and resulted in lower runoff and soil loss than the conventional tillage treatment, and required substantially less draught input but resulted in poorer weed control. The conventional tillage treatment provided good yields in wet years and poor yields in dry
years but good weed control. The implementation and characteristics of these basic tillage system types are described in detail in Section 3.1.

From the foregoing it can be seen that it is very important that the tillage system chosen is adapted to the expected climatic conditions, and that improved crop management must be available, and be implemented, to control the potentially increased levels of pest, weed and disease problems associated with some reduced and conservation tillage systems.

Elwell (1992) lists recent trials on large-scale farms reported by ART (1990), Winkfield (1992) and Oldrive (1989) which show that net returns per hectare from reduced tillage systems, and particularly those approaching zero-till, can be impressively better than conventional tillage.

2.5. ECONOMIC FACTORS

The various economic factors under which farmers operate, and in particular their resource base, is a major factor in the selection of tillage systems appropriate to their needs. This section will deal with some characteristics of farmers' households, the range of economic objectives of crop production, farmers' resource bases, and the various resources that need to be considered.

An important point that needs to be borne in mind is that the more deeply the farming systems being implemented by the farmers are investigated, the more apparent it is that many farmers are highly skilled at managing extremely limited resources. As Johnson (1988) points out, researchers and extensionists too often overlook the diverse and closely woven systems in which the resource-poor or subsistence farmers operates and come up with solutions that are inappropriate to them.

A large number of publications are available on the economic aspects of agricultural production, including several from FAO, plus Collinson (1983) on small-scale farmer risk strategies, and Buckett (1988) on farm organisation and management.

2.5.1. The Farming Household

Although discussion here will be limited to factors affecting soil tillage, it is important that extension workers consider the overall objectives of the farmer's household and the way in which it is run. The term household in this context is taken to mean the farm, house, buildings and equipment, the family living on the farm, and their immediate relatives who live on the farm but work off the farm or who send or take money or goods to or from the farm, and all the expenses and income from this whole group. It is important that extension workers do not limit themselves to only considering farming activities, because the financial and labour resources of the household are not only expended on farming activities. Although most extension workers are well aware of this and automatically include this fact in their considerations, it is considered important to emphasise it here.

Many farmers and their families are involved in work off the farm, and in many cases these activities provide the major income for the household. The main cash expenditure of a household may be school fees rather than the purchase of inputs for the farm. In some cases the farm is little more than a form of social security for urban-based owners, with mainly women, children and elderly relatives living and working on the farm. Depending on the cultural traditions this may result in the main decision makers and controllers of expenditure living off the farm. This can result in severe delays on management decisions and allocation of funds, and may indicate that tillage systems that require a high level of management may be inappropriate for these situations. These aspects are frequently ignored and result in
inappropriate tillage, cultivation and management systems being promoted. Alternatively, if the extension worker could facilitate improved decision making structures within the household, through drawing attention to the problems the old structures caused, this may be more effective than recommending adoption of a different tillage system. Hence, a broad overview of the whole situation that the farmers find themselves in is required.

2.5.2. **Crop Production Objectives**

As previously stated soil tillage is an intrinsic component of crop production and hence its objectives are also largely determined by the objectives of crop production. These objectives will vary from farmer to farmer with the commercial and subsistence farmer being at either extreme. As Buckett (1988) points out the crop production objectives of the commercial farmer with a limited area of land may be high profits per hectare, whereas commercial farmers with large farms may place more emphasis on return on capital and can consider less intensive systems. The crop production objectives of the subsistence farmer may be limited to the production of sufficient food for the household for one year with the minimum expenditure of cash and labour, and also importantly, with the minimum exposure to risk in terms of food supply and financial loss or gain. However, all farmers still desire to maximise returns over inputs, even though the inputs and desired returns may vary substantially from farmer to farmer.

For the above reasons it is important that extension workers identify the crop production objectives of the farmer and the available resource base, before moving on to identify and resolve any tillage problems that may exist. It is also important to determine whether the farmer's objectives are compatible with the available resource base, and if this is not the case then this should be resolved before proceeding. This generally can be done through discussion and observation and should not take long. It is generally not necessary to collect details of previous sales and purchases, etc., unless a detailed farm management plan is being prepared, and this is not usually the task of the extension worker.

2.5.3. **Risk Strategies**

Farming, as a business or a means of survival, is characterised by a relatively large input in terms of finance and labour, followed by a long period before the output can be harvested or sold. This relatively long-term investment combined with the vagaries of climate, pest infestations, etc., means that farming is generally a high risk business and this is particularly true in the arid and semi-arid regions. The climate is the main source of risk, with the main factors being the occurrence of short in-season droughts as well as long-term drought cycles.

Because of the above situation all farmers operate on the basis of taking risks with the investment of their existing financial and labour resource base. The level of risk that a farmer is prepared to take is based on three main factors:

- The security that the farmer has left if the investment is lost.
- The likelihood of the success of the investment.
- The level of return on the investment.

Resource-poor farmers have very little security left if their investment for the cropping season is lost and hence are not as prepared as resource-rich farmers to take risks. For resource-poor farmers the loss of the little that they have can result in extreme hardship or even starvation. Resource-rich farmers have a secure base and their main consideration is the likelihood of success of the investment and the level of return on the investment. They are in a better position to take risks provided there is a good chance that taking that risk will reward them. Many farmers will operate on a low or higher risk strategy on an intuitive basis rather
than verbalising the rationale for their decisions.

The resource-poor, or subsistence, farmer will rarely expend cash on crop production inputs. Their major input is labour and even the seed is frequently saved over from previous crops. Resource-rich and resource-poor farmers will have different attitudes towards expenditure on capital items, such as draught power sources and implements, and recurrent cost inputs, such as high yielding seed varieties, fertilizers, herbicides, pesticides, and the purchase of additional labour to improve timeliness of cultivation operations. A good example of this was given at the end of Section 2.4.1.3 in relation to the difference in approach to the application of fertilizers by resource-rich and resource-poor farmers. This example should be referred to again in light of the above points.

The various tillage systems have different implications for capital costs and recurrent costs and hence the level of resources of the farmer and the risk strategy that the farmer is operating on, even if only intuitively, must be taken into account. Several examples of this have already been given in the preceding sections. For example, if conservation tillage systems are to be promoted then the requirement for improved weed and pest control and their associated costs must be considered. It may not be in the interests of resource-poor farmers to expend the little financial resources they have on the purchase of equipment and chemicals if they are not guaranteed a good season. This is particularly true as many of the advantages of conservation tillage systems only become apparent after several years. However, the improved water conservation characteristics of the systems frequently pay dividends within the first year. If tied-ridging systems are to be promoted to improve water conservation and reduce erosion then the initial high installation costs must be considered, even though low cost reduced tillage systems are to be used in subsequent years. Resource-rich farmers are more likely than resource-poor farmers to take the risk in adapting to a new system and buying the required implements on the chance of higher crop production in subsequent years.

For resource-poor farmers the sustainability of their production is even more important than for richer farmers as they have few savings to fall back on if their crops fail, or yields gradually decline. Unfortunately, most of the farming systems they practice result in high soil and nutrient losses and so are not sustainable. The promotion of crop management systems that promote the sustainability of crop production, such as crop rotations and multiple cropping, is thus even more important amongst this group than amongst richer farmers. This is particularly true, as these crop management systems usually do not carry an increased cost with them, and in many cases cut costs. Although some forms of multiple cropping can pose problems for implementation on highly mechanised farms, these problems rarely occur on resource-poor farms as they are not highly mechanised. These crop management systems will be described in greater detail in Section 3.2.2.

2.5.4. Resources

There are many resources to be considered when selecting appropriate tillage systems or when considering alternative solutions to key restrictions in farming systems. These include resources such as financial resources and access to credit, land, labour, draught power, implements as well as less tangible resources such as management ability. It is important that other resources characteristic of the region rather than the individual farmer are also considered, such as general infrastructure, e.g. transport facilities, local service centres, retail outlets for purchase of farm inputs, etc. These usually apply equally to resource-rich and resource-poor farmers, and may be the main restrictions to higher crop production for both groups.

Further discussion on these resources will not be gone into here. The weed, pest and disease implications of the various tillage systems, and their associated costs, have already been discussed, and the draught power, labour and implement requirements of the various
tillage systems will be dealt with in later sections.

2.6. FARMERS’ PREFERENCES, SOCIAL INFLUENCES AND GOVERNMENT POLICIES

Farmers' preferences, social influences and government policies all affect the types of tillage and cultivation systems adopted by farmers. These aspects are covered by Unger (1984) and will be briefly covered here.

2.6.1. Farmers’ Preferences

The crop production practices of different farmers in a given area may vary widely for the same crop. As discussed in the previous section the different resource bases of the farmers explain some differences, however, other factors such as upbringing, education, pressure from neighbours or peer pressure and ambitions are also involved.

Tradition plays an important role in farming, primarily because most farming is a family enterprise with responsibility for farming activities gradually moving from the older to the younger generation. This situation favours the continuation of use of similar farming systems by successive generations. Education and extension are required to break into this cycle if the traditional systems are limiting and improved farming and conservation methods are to be adopted. However, it is important to emphasise that as farmers are familiar with managing their traditional systems, that new systems should be tried out on only a small proportion of their farms at first, until they are familiar with all the new skills required to implement the new system. If farmers put a large proportion of their farm under a new crop production system, without being familiar with its implementation, they are taking a severe risk and it is important that extension workers do not encourage this.

Pressure from neighbours and peers plays an important role in farming. In many farming areas there is strong pressure from these sources to maintain traditional farming systems. Less successful farmers will often see ambitious and successful neighbours adopting improved farming systems as an unwarranted challenge on their status and will be resentful of their success. This is a difficult problem and an important role of extension workers is to engender a constructive, helpful and progressive attitude amongst neighbouring farmers. The usual approach to this is through the organisation of field days and the sharing of solutions to specific problems.

Ambitious farmers are usually the least bothered by restraints from neighbours and peer groups, and are often the leaders in adopting new farming systems. An important means of extension is identifying these successful farmers in a particular area and using them as a focal point for extension to neighbours. Prior to doing this it is important to study their existing farming systems in detail and the manner in which they have adapted improved systems and to ensure that these are sound and sustainable. However, it is important that all farmers, and especially the poorer groups, are targeted for on-farm research and extension. As ambitious and successful farmers seldom belong to the resource-poor category, it is important that this latter group is also targeted. Again, the more successful and ambitious members of the resource-poor group are usually the most appropriate farmers to start working with.

2.6.2. Social Influences

The social influences on crop production practices are important and varied and include pressures from increasing human populations, cultural attitudes to livestock ownership, societal attitudes to resource conservation, etc.
Increasing population pressure affects crop production systems by demanding increased production from the same area of land, or frequently, a slowly diminishing land area. In many countries this intensification of production has lead to a reduction in the length of time that land can be left fallow. This pressure has been very harmful where soil fertility was maintained by the use of long fallow periods and where increased cropping was not accompanied by appropriate conservation measures, (FAO 1978).

In many cultures the amount of livestock owned by an individual is a measure of wealth and they also play an important part in various family transactions. This lack of a direct association between domestic animals and their agricultural use often leads to an imbalance between the amount of livestock and the carrying capacity of the land, and this results in overstocking and the degradation of grasslands. When the natural grasslands are no longer able to support the livestock the crop residues are often used as a supplementary fodder source. This in turn leads to a decline in the soil organic matter content of the soil when the crop residues are not returned, and may also exclude the use of conservation tillage systems which use crop residues to protect the soil from erosion. One aspect of this is that in many countries the cattle are grazed communally, and this includes crop residues on arable lands during the dry winter months. Under these conditions it is extremely difficult for the few farmers who may wish to retain crop residues on their lands to do so, as the others see them as depriving their livestock of food. Furthermore, the problem of keeping livestock off a few particular fields is difficult and the cost of fencing is high. Changes to these cultural attitudes are extremely difficult to achieve even though their harm to the environment may be apparent to all concerned. This is particularly true in those countries where the currencies are unstable and livestock is a relatively secure form of investment. Frequently all that can be achieved is to increase the carrying capacity of the land through improving the management of grazing and encouraging the production of fodder crops. If farmers can not be persuaded to retain crop residues for the protection of the soil then conservation tillage systems that do not require these should be considered, e.g. tied-ridging, however soil organic matter levels will still fall if no residues are returned. Multiple cropping and crop rotation systems designed to minimise erosion and nutrient loss should be considered, with as much retention of residues as possible.

In many countries the various pressure groups concerned with the maintenance of natural resources are an important means of spreading the message of the importance of the prevention of land degradation. The consistent work of the various extension organisations in most countries in promoting awareness of conservation is an extremely important means of gradually changing people’s attitudes to this extremely important subject.

2.6.3. Government Policies

Government policies can have a major influence on crop production systems, and can result in either promoting resource conservation or land degradation.

As Unger (1984) points out land degradation may result when local, state, regional or national government policies encourage crop production on lands susceptible to erosion that are not adequately protected by the use of suitable tillage systems or other conservation measures. Such production may be for domestic consumption or export, and may be encouraged through decrees, laws and the payment of subsidies. Land degradation may also result from policies which encourage or fail to prevent overgrazing and crop residue removal or burning, which permit the use of tillage and related practices that are not conducive to resource conservation, and which result in the introduction of poorly planned programmes.

However, the importance of resource conservation in order to ensure that agricultural production is sustainable has become increasingly apparent to governments over the years. Many governments have instigated resource conservation measures in their countries and the importance of strategy formulation to tackle problems in land degradation that involves many
different sectors was outlined in Section 2.2.3.

Unger (1984) goes on to make the following important points for the successful implementation of conservation plans. A prime requisite is the creation of awareness that a change is necessary on the part of the producer. Policy makers must be made aware of this need. Then all agencies concerned must work together as a team. To ensure adoption, education of and technical assistance to the producer are usually necessary. Also, assistance in the form of food or cash may be necessary so that adoption of the practices does not result in an undue financial burden on the producer. Adoption of the improved practices is a benefit to the entire country, not just to the producer on whose land the practices may be applied. These points emphasise the importance of developing a comprehensive strategy to tackle the problem of land degradation.

It is important to realise that many farmers will not adopt measures to improve conservation for its own sake. Furthermore, funds may not be available to assist in the adoption of improved practices, and anyway these may only be feasible for encouraging practices such as the construction of mechanical conservation works, rather than the use of conservation tillage systems. In these situations it is necessary to demonstrate to farmers the advantages that they will gain by using sustainable farming systems. Usually conservation tillage systems can be sold far more effectively through demonstrating the improved moisture retention characteristics of the system and the resulting yield increase, or the lower draught power inputs required, than through promising higher yields in the distant future through reducing erosion and improving the nutrient status of the soil.
3. TILLAGE, CULTIVATION AND MANAGEMENT SYSTEMS

The previous sections have dealt with the properties of soils, the various factors to be considered when selecting a tillage system appropriate to a particular situation, and the main factors to be considered when analysing problems relating to tillage. This was dealt with by a discussion of the properties of soils, how these properties affected other processes, e.g. rate of water infiltration, propensity to erode, etc., and how their properties and responses to other processes could be altered by different mechanical or cultivation interventions, e.g., soil loosening, increasing the soil organic matter content, provision of protection by crop residues on the surface, etc. The associated consequences of some of these interventions were also discussed. This section will draw together the main aspects of the detailed information given in the previous section and show how they interact in specific tillage systems. The ways in which the different cultivation and management systems can be used to complement the main attributes, or compensate for the main deficiencies, of the tillage system being used are also discussed.

The definitions of soil tillage, crop cultivation and management systems used in this report are based on those used by Unger (1984):

- **Soil tillage** is the mechanical manipulation of the soil within a crop production system. A soil tillage system is the combination of a group of tillage operations that together make up a coherent tillage system.
- **The term crop cultivation systems** cover the way in which the cultivation of the crop is implemented. There are two main types of crop cultivation systems, namely, traditional shifting cultivation and continuous cultivation. Unger (1984) divides the means of implementation of cultivation systems into the following; manual; animal and small tractor; and large tractor and high technology systems.
- **The term crop management systems** embrace all tillage, planting, fertilizing, weed, pest and disease control, water control, and harvesting operations. It also includes crop rotations and multiple cropping.

No tillage, cultivation or management system can meet all the requirements of a particular farmer operating on a particular farm within a particular socio-economic framework. Every system is going to be a compromise, but the main requirements of the farmer must be met by the system and the disadvantages must be able to be managed by the farmer. Both the long-term sustainability of the system must be considered as well as the short-term consequences to the farmer of the implementation of the system, especially in terms of financial risk and the reliability of producing a crop. The exact details of the tillage system, or crop rotation, etc., to be used cannot be given here as these depend on the local climate, soil type, resources of the farmer, infrastructure, etc. Readers should refer to earlier relevant sections in this book for a detailed coverage of the rationale behind, and implications of, the various choices outlined in this section.

3.1. TILLAGE SYSTEMS

Tillage systems are categorised primarily according to the level of intensity of the tillage operations used in the implementation of the system, and the extent to which they are geared towards the conservation of soil, water and energy. The basic categorisation used in the introduction will be used here, i.e. convention, reduced and conservation systems. As there are a large number of different systems only those that are broadly typical of their type will be described here.

The conventional tillage system is described because it is now the most widespread mechanised system and the one from which most other mechanised systems have been developed. The strip tillage without mulch tillage system is described because it is a system in
fairly common usage that has been developed primarily to address the constraint of poor draught power availability and lack of crop residues, however it has several serious disadvantages in terms of sustainability. The reduced-till tied-ridging system and zero-till system have been described as they are two very different tillage systems, the latter in reasonably common use, which meet the objective of sustainable crop production, but can present significant and very different problems in their implementation.

The above tillage systems are similar to those under on-station trials in Zimbabwe on sandy soils. The trials are being implemented using animal draught and are appropriate to farmers in the small-scale farming sector. However, the results are equally applicable to the use of tractor drawn implements. The trials are primarily concerned with the yield and the soil and water loss of the different tillage systems. All relevant soil condition parameters are being measured. The trials started in the 1988-89 season and are due to run for 7 or more years. On-farm trials are being run in parallel to study the labour requirements and the difficulties that the farmers encounter in the implementation of the systems. Some preliminary finding were summarised in Section 2.4.5.

The implementation of the tillage systems will be described, together with the general characteristics of the systems, e.g. runoff and soil loss, and the most important cultivation aspects, e.g. the associated weed and pest problems. Detailed descriptions of all the characteristics mentioned are given in Section 2. The objectives and methodologies of how to implement the specific tillage operations are given in Section 5.

At this stage no major distinctions will be drawn between the draught power source, whether this be animals or small or large tractors, when describing the tillage systems. This is because the various tillage systems can be implemented using any of these draught power sources. Although on hard soils some tillage operations can only be implemented using large tractors, e.g. deep subsoiling operations, most tillage operations can be implemented using either animals or large tractors as the draught source. The difference between the draught power sources affects primarily the rate of work rather than the quality of work and hence yield, provided the operators and animals are well trained, and the implements are in good condition. Furthermore, many of these tillage systems can be implemented using only manual labour. However, both with respect to quality of implementation and rate of work, the improvement of moving from the use of manual labour to animal draught power is much larger than in moving from animal to tractor draught power. These aspects will be discussed further in Section 5. As the cultivator, harrow and hoe are generally used for fairly similar operations generally only the cultivator will be mentioned in the following sections.

3.1.1. Conventional Tillage Systems

Conventional tillage systems involve intensive tillage operations with any remaining crop residues fully incorporated into the soil. This involves full depth ploughing with complete inversion of the soil, one or more cultivation operations prior to planting, and cultivation and/or herbicide weed control. The only conventional tillage system to be described in detail will be the full primary and secondary tillage system on the flat. Some supplementary tillage operations used with this system are described in the next section.

3.1.1.1. Conventional Tillage System on the Flat

The conventional tillage system without beds or ridges, implemented with full primary and secondary operations, is the tillage system most commonly used by farmers in all agro-ecological regions where animal or tractor draught power is available. The only major exceptions to this are those regions where paddy rice systems predominate.
Historically this tillage system was developed primarily to control weeds in the temperate regions prior to the development of herbicides, and the main positive attribute of this system is that good weed control can be achieved without the need for herbicides. Furthermore, pest control is generally easier with this system than with others. These two attributes are of crucial importance to many farmers and especially to many small-scale farmers. However, the erosion potential of this system is high and the soil organic matter levels are generally low. The system should generally not be used where there is high erosion potential. The implementation of the system, together with the main objectives of the operations, are given below:

A. Implementation, objectives of operations and notes:

Note: The following steps should ideally be implemented during the first year of the conventional tillage system:

- Correct any uneven soil surface resulting from faulty ploughing in the past or inherent unevenness, which would result in an uneven distribution of water over the field. Use corrective ploughing measures, damscoops or land-planes.
- Correct any compaction problems that would restrict root growth or infiltration.
- Incorporate crop residues, manures, lime and fertilizers to improve soil organic matter levels, to correct pH levels and to improve nutrient levels, respectively.
- Control weeds through full inversion ploughing and good weed control throughout year.
- Control pests through good control throughout year.
- Planting rows should be slightly off-contour, parallel to the contour ridges.

• Stubble or post-harvest operations:
  - Shallow tillage carried out with a cultivator shortly after harvest:
    . To modify soil structure: To break the capillary continuity of the soil surface with lower levels so as to reduce loss of soil water through evaporation and to provide a soil mulch; to roughen surface and to restore soil structure to increase water infiltration, if any rain; to roughen surface and restore surface soil structure to reduce wind erosion, if a problem.
    . To control weeds: To reduce the carry over of weeds to next crop; to reduce soil water loss through plant evapotranspiration; to reduce pest population living on weeds.
  
  Note: Depth of tillage: As deep as necessary to obtain uniform control of weeds, depends on surface uniformity, and establishment of soil mulch; roughly 5 cm.
  Note: Time of tillage: If the main objective of the above operations is to preserve soil water then the crop should be harvested soon after maturity and dried off-field to allow early implementation of tillage operations.
  - The above operations may be supplemented with chemical weed and pest control.

• Primary tillage:
  - Deep tillage with subsoiler:
    . To correct compaction problems, which restrict plant root growth and limit water holding capacity.
  
  Note: Depth of tillage: Depends on depth of compacted layer and depth of mature crop roots; usually 30 to 40 cm.
  Note: Deep subsoiling operations consume a lot of energy and should not be carried out on a regular annual basis. If compaction problems occur regularly then tillage operations should be changed so as to avoid compaction.
  - Deep tillage with mouldboard or disc plough parallel to the or slightly off-contour:
    . To modify the soil structure in the main rooting area of the next crop: To improve soil structure and increase surface roughness so as to increase infiltration rate and reduce runoff; to increase porosity and fracturing so as to
increase water holding capacity of the soil; to reduce compaction within plough depth and to increase porosity so as to allow easier root development.

To control weeds: To reduce competition of weeds with future crop for water, nutrients and light, (complete inversion of soil is very effective in controlling weeds).

To incorporate crop residues.

To incorporate nutrients and fertilizers.

To prepare land for seedbed preparation.

Note: Depth of tillage:

- As ploughing results in the loss of soil moisture the depth is primarily dependent on the amount and type of precipitation, generally the lower the precipitation the shallower the depth but always deeper than depth of seed placement. However, as the water holding capacity of the soil increases with increasing plough depth and as the amount of time to runoff increases with increasing holding capacity, potential erosion is reduced with increasing plough depth. Hence in regions prone to thunderstorms ploughing to reduce erosion should be deeper. The depth is generally 10 cm to 25 cm.

- Depth of ploughing should be varied each year so as to reduce the possibility of creating a plough pan.

Note: Time of tillage: This depends on a number of factors that have been discussed in relevant sections previously, some of which are summarised below:

- On clay soils ploughing should be carried out a sufficient length of time before seedbed preparation to allow weathering to promote a good soil structure. However, this needs to be balanced against loss of soil moisture in arid and semi-arid regions.

- Ploughing should be carried out at a time which allows planting to be carried out at the start of the season, this is particularly important where season length is a limiting factor to yield. However, in regions where there is a long dry season the soils can be very hard and the animals in poor condition to plough just before the start of the rains. If resulting yield losses from delayed planting are significant, and if the use of tractor draught power is not appropriate, then reduced tillage or autumn ploughing should be considered.

- Ploughing at the end of the rainfall season (autumn ploughing) ensures soil is at the appropriate moisture content to minimise draught force requirements, and the conditions of draught animals is also at a peak at this time of year. However, in regions where there is a long dry winter then autumn ploughing can result in all soil moisture within rooting depth being lost. If however, the long dry winter is so long that all moisture would be lost however the soil was managed then this proviso is removed. If autumn ploughing is carried out then this takes the place of the stubble or post harvest tillage operations. To limit moisture loss in arid areas ploughing should be followed immediately by shallow tillage to provide a finer soil mulch over the ploughed layer, unless weathering is desired as described above.

- In cold regions where the length of season is restricted by low soil temperatures at the start of the season, ploughing can be used at the start of the season to speed the warming of the topsoil.

- Seedbed preparation:

  - Shallow tillage with cultivator:
    
    - To modify the soil structure down to planting depth to a fine tilth to facilitate germination and emergence.
    
    - To control weeds prior to planting to reduce competition with crop for water, nutrients and light, and to reduce food source for some pests.
To incorporate any herbicides and pesticides applied.

- Rolling to firm seedbed, (not always included):
  - To increase density to improve seed/soil contact to facilitate germination.
  
  Note: Seedbed should be prepared before the start of the season, for reasons given under time of ploughing.
  
  Note: Size of soil aggregates in well aggregated soils, e.g. clay soils, should generally be roughly 1 to 5 mm in size depending on seed size to ensure good seed/soil contact.

- Planting and fertilizing:
  - Planting and fertilizing:
    
    Note: Fertilizer applied with seed for resource-rich farmers when fair chance of poor season to maximise yield in case of good season. Fertilizer not applied with seed for resource-poor farmers when fair chance of poor season to conserve resources. For latter farmers the fertilizer is applied, if at all, if good season develops.
    
    Note: To reduce possibility of burning the seed banded fertilizer should generally be placed 5 cm to the side and 5 cm below the depth of seed placement.

- Crop management operations:
  - Shallow tillage with cultivator
    - To break up surface crusts to aid crop emergence and to improve water infiltration.
    - To control weeds.
    
    Note: Depth of tillage: Shallow and specialised to break crust without damaging seedling. Roughly 5 cm for control of weeds.
    
    Note: Frequency of tillage: Dependent on efficient weed control and propensity of the soil to crust. In highly crusting soils shallow tillage may be required after each heavy rainfall to promote infiltration.
    
    - Some chemical weed control may supplement tillage operations.
    
    - Chemical pest control usually required.
    
    Note: Control of weeds and pests during cropping season is very important so as to reduce carry over to post harvest period and next season.

B. Characteristics of the Tillage System.

- Soil structure:
  - Soil structure is restored prior to planting each year and hence porosity at the start of season is good. However, due to generally low soil organic matter levels the level of soil aggregation is low and the proportion of aggregates that are water stable is low, resulting in the soil having low structural stability. This combined with frequent tillage passes frequently leads to compaction problems.
  
  - Lack of protection of the soil surface by crop residues, together with low levels of water stable aggregates, facilitates crusting problems due to raindrop impact, necessitating frequent corrective shallow tillage.

- Soil water:
  - Infiltration: During the first rains infiltration is good due to freshly cultivated soils. However, the lack of protection of the soil surface by crop residues facilitates crusting, especially as the proportion of aggregates on the surface that are water stable is low. Hence the infiltration rate decreases sharply during each rainfall event. On crusting soils shallow tillage may be required after each rainfall event to maintain infiltration at acceptable levels.
  
  - Water holding capacity: This is good at the start of the rains due to high porosity down to full plough depth. This declines as the season progresses due to low structural stability.
  
  - Evaporation:
    - Full depth ploughing encourages the loss of existing soil water in the
plough depth zone because the soil is inverted bringing the moist layers to the surface and the porosity of the tilled layer is high. Water loss due to ploughing is exacerbated if it is followed by a long dry spell, and also if shallow tillage to provide a fine tilth to act as a dust mulch over the ploughed layer is not carried out immediately after ploughing. Because of this full depth ploughing and full inversion of the soil results in low levels of soil moisture at the end of a long dry season and at the start of the rainfall season. In arid areas this leads to planting conditions being critically dependent on subsequent rainfall. The start of the growing season may therefore be delayed while the soil moisture levels build up to acceptable levels for planting or germination. The timing of ploughing is important to minimise the large moisture loss in arid areas.

Shallow tillage to break the capillary continuity between the surface and lower layers, and to provide a dust mulch is the most effective means of reducing evaporation from the subsoil over long dry periods. In this tillage system this is carried out during the season, mainly during weeding, and especially immediately after the harvest in arid areas.

Erosion potential:
- The erosion potential of this system is high. However, with the first rain event it is low, (unless precipitation duration is long and intensity is high), because the soil surface is initially rough allowing a high infiltration rate and surface water holding capacity, (unless too fine a tilth for the seedbed or dust mulch has been created), and so total infiltration is high and runoff is low, resulting in low erosion. However, for soils with no crop residue protection or growing crop protection at the start of the season, and with a low level of water stable aggregates, the surface soil rapidly starts to cap resulting in a rapid decrease in infiltration rate, an increase in runoff and a resultant increase in erosion. Unless the surface soil structure is restored through tillage after each significant rainfall event has occurred, the erosion potential of this system is high.

Soil organic matter:
- The rate of decomposition of buried crop residues is higher than that of residues left on the surface. These decomposed components are then incorporated into the soil structure as soil organic matter. However, the frequent tillage operations aerate the soil and speed up the decomposition of the soil organic matter as well, and usually at a higher rate than it is being formed from the crop residues. Unless large quantities of crop residues are incorporated each year the soil organic matter levels in this system will gradually decrease to a low stable level. This low level of soil organic matter leads to problems in soil structure, capping, low infiltration rates, high erosion potential, etc., as described above, and to poor nutrient characteristics, described below.

Nutrient requirements:
- If crop residues are being fully incorporated during ploughing then during their decomposition nutrients will be released into the soil. This results in lower levels of additional nitrogen being required in this system than in conservation tillage systems, where the decomposition of crop residues is slower and little nitrogen is released. However, because of the low levels of soil organic matter the sites of fixation on the clays will not be saturated and some fertilizers, and especially phosphates, will be bonded to the clays and will not be available to the plants. This necessitates higher levels of some fertilizers than in conservation tillage systems. On sandy soils, under conventional tillage systems, there is little to hold the fertilizers in the soil due to the lack of clays and the lack of soil organic matter. The resultant leaching of fertilizers from sandy soils is a major problem under this tillage system unless large quantities of crop residues are returned.

Seed germination and emergence:
- Under humid conditions seed germination is good because good seed/soil contact can easily be achieved with this system. Under arid conditions the
surface soil layer can dry out rapidly due to lack of crop residue cover and can result in germination problems. Deeper planting of the seed in arid areas is therefore required. However, the poor water conservation characteristics of this system limit good germination and emergence in this system in arid areas. The lack of crop residue cover encourages capping problems and this can inhibit good emergence. However, this problem can be overcome using specialised shallow tillage prior to emergence.

Weeds:
- One of the main positive attributes of this system is that good weed control can be achieved without the need for herbicides, which is a crucial factor for many small-scale farmers. However, weed control using tillage only is labour and energy intensive, especially if draught power is not available. The control of weeds before they become established is very important. This usually means destroying the weeds before they reach 5 cm in height.

Pests and diseases:
- Another of the main positive attributes of this system is that the carry over of pests and diseases from the previous crop is minimised because crop residues are removed, or covered by ploughing that usually destroys all the pests and diseases in the residues. The destruction of crop residues combined with good weed control removes the pest species food supply and habitat for large proportions of the year which also limits pest infestation levels.

Harvesting:
- The lack of crop residues facilitates harvesting of crops with a low stature.

Energy inputs and power requirements:
- The total energy inputs are high due to the high energy requiring primary tillage operation and the numerous secondary tillage operations. The power requirements for the primary tillage operation are high, especially when these are carried out at the end of a long dry period. Draught cattle at the end of a long dry winter are also in their weakest condition. These are some of the main reasons why alternative tillage systems have been developed.

Equipment requirements:
- As this is the conventional tillage system tillage equipment has been designed for this system for a very long time. The lack of crop residues on the soil surface also facilitates the use of simple equipment for all operations.

Economic characteristics:
- Profitability:
  - Input costs: The costs of implementing the tillage operations are high. Costs of weed, pest and disease control is generally lower than other systems. Fertilizer costs increase as soil becomes nutritionally depleted.  
  - Yield: With adequate management yield is not suppressed by weed and pest problems. Yield is good with adequate rainfall, and poor in inadequate rainfall seasons.  
  - Risk: Risk is high in regions prone to droughts as well as on lands prone to soil erosion.

Further details of the above points can be obtained from the relevant sections in Section 2.

3.1.1.2. Supplementary Operations to the Conventional Tillage System on the Flat

Some of the drawbacks of the conventional tillage system implemented on the flat can be overcome by using additional tillage operations. However, it should be noted that these operations require additional energy for their implementation.

A. Ridging and Tied-Ridging
One of the main drawbacks of the conventional tillage system on the flat is its poor water conservation aspects in arid and semi-arid regions and its high erosion potential. These major drawbacks can be overcome very effectively by using ridges constructed slightly off-contour and especially by tied-ridges. The detailed methodology for the implementation of this tillage operation is given in Section 5. Planting is usually carried out on top of the ridges. The ridges and ties are constructed such that generally all the precipitation is retained where it falls, allowing all the water to infiltrate even if the rate of infiltration is low. In the event of the total precipitation being very high and overflowing the ties, which are constructed to a half to two thirds the height of the ridge, then the water flows slowly down the slight gradient at which the ridge is laid, and this minimises erosion. The system must be designed so that there is no chance of water accumulating in the furrows at the lowest point on uneven land and breaching the ridges. In order to achieve this on uneven land it is important that the land is levelled as much as possible and that the ridges are laid on a steeper slope than on even land. The major drawback of this system is the high energy input required to construct the ridges each year. However, this problem can be substantially reduced by using a reduced tillage version of this system and a detailed example of this is given in the next section.

B. Micro-Catchment Tillage

A variation of the above system is called micro-catchment tillage, used in areas of very low rainfall. In this system widely based furrows are made and these are dammed and the crop is planted in the bottom of the furrow or basin. The system was found to function well on the vertisols providing excessive precipitation did not occur, as this led to waterlogging problems. On very shallow sandy soils the system was not found to be satisfactory as the topsoil depth was inadequate at the bottom of the furrow. This was overcome to some extent by the banding of manure in the furrow bottom. A high draught energy input is required for this system and the large number of tillage operations required also leads to a loss of soil organic matter.

C. Pot-holing

Another tillage operation which can be used to improve the water conservation aspects of conventional tillage systems is pot-holing. This system also reduces erosion to some extent by reducing runoff. Pot-holing involves the digging of a line of depressions in between the plant rows to hold water on the surface during precipitation and so reduce runoff and increase the time available for infiltration and hence total infiltration.

D. Precision Strip Tillage

Tillage systems designed to limit compaction to specific paths through the field are known as tramline tillage or precision strip tillage. In these system all machinery or animals are limited to travelling on the same paths each time they carry out operations in the field. Although compaction in these tracks is high, there is no machinery or animal induced compaction between the tracks in the plant rows. Because of the difficulty of keeping to these lines if the system is used on the flat, ridges or beds are commonly used with this system. In these systems it is important that the tramlines, or beds, are laid slightly off-contour so that any excess water flows slowly down these tracks and does not accumulate at the lowest point on the track in uneven land and so breach the beds.

3.1.2. Reduced Tillage Systems

Reduced tillage systems use fewer tillage operations than conventional tillage in order to reduce the energy input required, and sometimes to reduce soil disturbance. Primary tillage operations do not usually include the use of mouldboard or disc ploughs, or at least not every
cropping season. Crop residues may be removed or partially incorporated. Generally any crop residues left on the surface cover less than 30% of the surface area, otherwise the system is classified as a conservation tillage system. Two reduced tillage systems with very different characteristics will be described, namely, strip tillage without mulch and reduced-till tied ridging. The first system is described by Norton (1987) and Vogel (1992), and by Willcocks (1981) although with the use of crop mulches, and the second by Elwell and Norton (1988) and Vogel (1992).

3.1.2.1. Strip Tillage Without Mulch

This system involves widely spaced shallow ripping parallel to the contour ridges without the retention of crop residues. Farmers commonly use it who have limited access to draught power, usually animal draught power, and where the crop residues are normally fed to livestock. The advantages of the system are the reduced draught power requirement and time required to implement the system, and hence the improved timeliness of planting. However, the disadvantages include a high erosion potential, similar to that of conventional tillage on sandy soils, poor water conservation after the first few rains, although again similar to that of conventional tillage systems, low soil organic matter levels, and weed control problems. The system should generally not be used where there is high erosion potential.

The implementation, objectives of the operations and the characteristics of the system are listed below. Some minor modifications to the commonly implemented system are given to reduce the erosion hazard to some extent. Where the operations and objectives are similar to those in the previously described conventional tillage system, the detailed objectives and notes will not be repeated, and hence these should be referred to for completeness.

A. Implementation, objectives of operations and notes:

YEAR 1.

Note: The standard conventional tillage system should be implemented in the first year of this system in order to ensure that the system starts with good weed control and with maximum incorporation of crop residues to maintain soil organic matter levels. The conventional tillage system should also be reverted to occasionally to control weeds and incorporate organic matter, nutrients and fertilizer. Planting rows should be slightly off-contour, parallel to the contour ridges. The following steps should ideally be implemented during the first year of the conventional tillage system:

- Correct any uneven soil surface resulting from faulty ploughing in the past or inherent unevenness, which would result in an uneven distribution of water over the field. Use corrective ploughing measures, damscoops or land-planes.
- Correct any compaction problems which would restrict root growth or infiltration.
- Incorporate crop residues, manures, lime and fertilizers to improve soil organic matter levels, to correct pH levels and to improve nutrient levels, respectively.
- Control weeds through full inversion ploughing and good weed control throughout year.
- Control pests through good control throughout year.
- Planting rows should be slightly off-contour, parallel to the contour ridges.
- The conventional tillage system may need to be reverted to occasionally to correct pH problems, through incorporating lime, to correct compaction problems on high density soils, and to control weeds and pests. If this is done not all the accumulated benefits of the reduced-till system to the soil will be lost.

YEAR 2.

Stubble or post-harvest operations:
Crop residues removed from field and stored for livestock, but the plant bases and roots left in the soil:

- To reduce soil compaction in the field by grazing livestock and to improve control of fodder supply.
- To reduce carry over of pests in crop residues in the field.
- Plant bases and roots retained to bind soil and roughen surface to reduce erosion.

- Very shallow inter-row and within-row tillage carried out with a hand hoe shortly after harvest:
  - To modify soil structure and retain soil water.
  - To control weeds.

Primary tillage:

- Deep parallel tillage in the old inter-row, on-contour or parallel to the contour ridge, with a ripper tine or chisel plough:
  - To modify the soil structure in the main rooting area of the next crop.
  - To retain old plant bases and roots to bind soil and roughen surface.
  - To trap runoff from untilled areas, hence tillage is on-contour.
  - To partially control weeds.
  - To incorporate nutrients and fertilizers.
  - To prepare land for strip seedbed/planting.

Note: Depth and spacing of tillage:

- Depth usually 150 cm, but deeper if deeper compaction layer. A depth of 150 cm results in a width of roughly 173 cm of surface soil being disturbed (2 x depth x tan 30 deg.). Width of spacing for widely spaced crops such as maize would be roughly 900 cm, and would result in 19% of the soil surface being disturbed. For narrow spaced crops this would obviously be higher.

- Note: Time of tillage: Must be carried out before the start of the rains to reduce erosion potential. Similar to conventional tillage but with following exceptions:
  - Sandy soils should be ripped when fairly dry to aid fracturing of the soil. Usually carried out shortly before the start of the rains.
  - Clay soils can become very hard when dry and so should be tilled when moister than sandy soils, in order to achieve required depth of tillage. Should still be dry enough to fracture when tilled. Autumn tillage may be required.

Seedbed preparation:

Note: Separate seedbed preparation not normally carried out.

Note: Weed control immediately prior to planting is important. This is normally carried out using a hand hoe, however, if animal draught power is available then a spike tooth harrow is effective if weeds are small and it has a high work rate.

Planting and fertilizing:

- Planting, fertilizing and adding humus using hand hoe direct into rip line:
  - To improve the seed/soil contact, as seedbed preparation not previously undertaken, hoe should be used to produce fine tilth in planting hole, and manure/decomposed organic matter added to below seed level.

Crop management operations:

- Very shallow tillage with hand hoe:
  - To break up surface crusts to aid crop emergence and to improve water infiltration.
  - To control weeds.

B. Characteristics of the Tillage System.

Soil structure:

- Soil structure in the planting row is restored prior to planting each year and hence porosity at the start of season is good. However, due to generally low soil organic matter levels the level of soil aggregation is low and the proportion of
aggregates that are water stable is low, resulting in the soil having low structural stability. However, as most operations are carried out manually, or with animals, this does not generally lead to compaction problems.
- Lack of protection of the soil surface by crop residues, together with low levels of water stable aggregates, facilitates crusting problems due to raindrop impact, necessitating frequent corrective shallow tillage.

Soil water:
- Infiltration: The untilled surface in this system acts as a rain runoff area with the water infiltrating into the rip lines. When only the plant line is ripped most of the rainfall infiltrates into this zone. Infiltration in the rip lines during the first rains is good due to freshly cultivated soils. However, the lack of protection of the soil surface by crop residues facilitates crusting, especially as the proportion of aggregates on the surface that are water stable is low. Hence the infiltration rate decreases sharply during each rainfall event. On crusting soils shallow tillage in the rip lines may be required after each rainfall event to maintain infiltration at acceptable levels. As infiltration is primarily limited to the rip lines, and as these cover only 19% of the surface area, during heavy storms runoff may be high, resulting in high soil and water loss. However, the increased surface roughness and improved soil binding due to the retention of the old crop bases and roots may reduce runoff and soil loss to less than that for conventional tillage systems. During light rainfall the water is concentrated in the planting rows where it is needed especially during early plant growth.
- Water holding capacity: This is generally poor due to the low volume of the soil tilled and the poor structural stability of the soil.
- Evaporation: As the soil is not inverted during primary tillage and as only a small percentage of the volume of the soil is tilled down to primary tillage depth, soil water evaporation due to primary tillage is low. This leads to potentially higher soil moisture content at the start of the season compared to conventional tillage systems. Shallow tillage to break the capillary continuity between the surface and lower layers, mainly undertaken during weeding operations and especially immediately after the harvest in arid areas, is required to keep evaporation low.

Erosion potential:
- The erosion potential of this system is high. Infiltration occurs primarily through the surface area disturbed during the ripping operation and this covers less than 20% of the surface. However, if the old plant rows are retained and ripping is only carried out in the old interrow line then this leaves the roots and bases of the stems of the old crop intact, and hence provides stability to the soil and increases surface roughness which reduces the erosion potential of the system. As the structural stability of these soils is low and as crop residues are not retained on the surface capping is a serious problem. Surface soil structure should be restored through shallow tillage after each significant rainfall event has occurred.

Soil organic matter:
- Soil organic matter levels are low because crop residues are not generally retained as they are fed to livestock. However, the widely spaced and non-inverting primary tillage operation and the very shallow weeding operations minimise aeration of the soil, and hence the rate of decomposition of the existing soil organic matter is low. Incorporation of organic matter such as manure during planting and incorporation of residues during the conventional tillage cycle will increase soil organic matter levels slightly.

Nutrient requirements:
- These are generally similar to the conventional tillage system. However, due to the lack of retention of crop residues no nutrients are available from them,
Seed germination and emergence:
- Poor seedbed preparation, and the lack of crop cover and the poor structural stability of the soil leading to capping problems, generally leads to poor germination and emergence. However, care during planting to create a good tilth, and tilling to overcome the capping problems can overcome these disadvantages. Furthermore, this system is much better than the conventional tillage system in terms of reduced loss of water through evaporation, and hence more soil water is generally available at the start of the season. This, combined with the runoff from the untilled surface area into the planting row, gives an advantage to this system over the conventional system in times of low rainfall at the start of the season.

Weeds:
- The control of weeds in this system is more difficult than in conventional tillage as ploughing does not control them. Their control at the start of the season is particularly important if weed growth is not to get out of hand. Weeds should be destroyed before they become established and this usually means destroying the weeds before they reach 5 cm in height.

Pests and diseases:
- One of the positive attributes of this system is that the carry over of pests and diseases from the previous crop is minimised because crop residues are removed.

Harvesting:
- The lack of crop residues facilitates harvesting of crops with a low stature.

Energy inputs and power requirements:
- The relatively low total energy input of this system is the main reason it is used.

Equipment requirements:
- A ripper tine, chisel plough or ard is used for primary tillage and conventional equipment for the rest of the tillage system.

Economic characteristics:
- Profitability:
  - Input costs: The costs of implementing the tillage operations are low. Cost of weed control is generally higher than in the conventional tillage systems. Fertilizer costs increase as soil becomes nutritionally depleted.
  - Yield: Yield is suppressed by increased weed problems unless management improved compared to conventional tillage systems. Yield is good with adequate rainfall, and poor in inadequate rainfall seasons.
  - Risk: Risk is high in regions prone to droughts.

Further details of the above points can be obtained from the relevant sections in Section 2.

3.1.2.2. Supplementary Operations to Strip Tillage Without Mulch

The main drawbacks of the strip tillage without mulch system are its poor soil organic matter levels, poor overall water infiltration and retention characteristics, and high erosion potential.

A. Strip Catchment Tillage

The above drawbacks can be overcome if sufficient crop residues can be retained on the surface. When more than 30% of the soil surface is covered with crop residues the system is classified as a conservation tillage system, as the tillage input is still fairly low. However, even where this amount of crop cover is not available, the retention of residues on the surface together with the tillage operations can substantially reduce the above drawbacks. Furthermore, ripping slightly off-contour only on the plant row concentrates water into the plant
row, which is desirable in arid areas during early plant growth. This system has been called strip catchment tillage and is described by Willcocks (1981). Elwell (1992) recommends that with this system the rip line for the new planting row should be in the old inter-row position. This leaves the roots and bases of the stems of the old crop intact, and these provide stability to the soil and roughen its surface, which reduces the erosion potential of the system even further. If this is done care would need to be taken that pests, such as cutworms, which live in the base of some plants, e.g. maize plants, are not likely to become a problem. If they are then the bases should be knocked over.

B. Pot-holing

Limited pot-holing using hand hoes during weeding, or animal drawn pot-holers, could be used on an inter-row rip line to increase surface water holding capacity and hence total infiltration.

3.1.2.3. Reduced-Till Tied-Ridging

Ridging, or lister ploughing, is a commonly used conventional tillage system, with planting usually being carried out on the ridges, or sometimes in the furrows in arid areas. The ridge system was first developed in the humid climates of Europe for poorly drained soils, with the raised ridge providing an area of well-drained soil in which the crop could be planted. In tropical and subtropical regions subject to high intensity storms, the system has been used to reduce the amount and speed of runoff and hence to reduce erosion, by the use of gently graded furrows. The ridges are laid out slightly off contour or parallel to the contour ridges. In arid areas, and particularly on soils subject to capping, tying the ridges, or damming the furrows is used to modify the system. This increases the surface water holding capacity of the system, which increases the amount of time available for infiltration to take place, which increases total infiltration and further reduces runoff. If waterlogging problems occur then the ties are broken to reinstate the good drainage properties of the original system. The flexibility of this system to both conserve water and to have good drainage characteristics is highly desirable in areas prone to high and low rainfall periods during a season.

In the reduced tillage system full ploughing is usually carried out in the first year followed by the building of the ridges. In subsequent years only re-ridging operations, which are also used to control weeds, are carried out, so as to reduce the energy input and to reduce soil disturbance. Over 4 years the total draught power input is roughly half that of the conventional tillage system. Ploughing may be required after 4 to 6 years, particularly on sandy soils, to incorporate increased levels of organic matter and to rectify possible nutrient problems.

Of all the tillage systems that do not retain crop residues on the surface this system has the best soil, nutrient and water conservation characteristics, together with good drainage characteristics and good weed and pest control characteristics. This system should therefore be carefully considered for use. However, besides the initially high draught power requirement there are two further reservations pointed out by Elwell and Norton (1988). Firstly, in arid areas and particularly on sandy soils there is the possibility of the ridge drying out rapidly, and this is a seriously limiting characteristic especially during early crop growth. From on-going trials on sandy soils in Zimbabwe, Vogel (1992) has also found that poorer or delayed seed germination occurs as well as poorer seedling establishment. This was due to higher soil temperature and lower soil water levels in the elevated ridges than the other treatments. Secondly, the system should not be used on uneven land, as the furrows concentrate the water at low points in the land and if the ridges are breached this can lead to severe gulley erosion. The land surface must be sufficiently smooth to allow the crop ridges to flow without a maximum ridge gradient of 1 in 100 being exceeded. Lands badly incised by past erosion, or with uneven surfaces as a result of bad ploughing, should be smoothed before they can be used safely. Smoothing can be done by corrective ploughing, by dam scoop or by land plane.
This system should only be used on lands on which full mechanical conservation works have been laid out, i.e. storm drains, waterways and contour ridges. This is because in this system water is concentrated into the furrows and during heavy storms any runoff will therefore be concentrated at the end of the furrows, rather than running off the land fairly uniformly. If this concentrated runoff is not controlled by the conservation works it can lead to gulley erosion. The implementation of the system is described in detail by Elwell and Norton (1988), and a summary of the implementation, together with the main objectives of the operations, is given below. The method of how to peg out and make the ridges is given in Section 5.

A. Implementation, objectives of operations and notes:

YEAR 1.

Note: The following tillage and soil movement operations should be carried out prior to the start of the reduced-till component of this system:

- Ensure that all required storm drains, contour ridges and waterways are installed.
- Correct any uneven soil surface resulting from faulty ploughing in the past or inherent unevenness, which would result in the accumulation of water in the furrows and possible breaching of the furrows. Use corrective ploughing measures, damscoops or land-planes.
- Correct any compaction problems which would restrict root growth or infiltration.
- Incorporate crop residues, manures, lime and fertilizers to improve soil organic matter levels, and pH and nutrient levels, respectively.
- Control weeds through full inversion ploughing and good weed control throughout year.
- Control pests through good control throughout year.
- The conventional tillage system may need to be reverted to occasionally to improve soil organic matter and pH levels.
- Fields should be fenced off or arrangements made to keep livestock out of the fields after harvest.

Stubble or post-harvest operations:
- Crop residues removed from field and stored for livestock:
  - To facilitate the construction of ridges.
  - To reduce compaction by grazing cattle.
  Note: If ploughing to a depth of at least 250 mm can be carried out, (usually implies use of tractor draught power), then it is desirable to leave all the crop residues in the land and to bury these during ploughing to below the depth to which the ridger will operate. As not every field will be ploughed each year this will still leave crop residues from other fields available for fodder. This will assist in raising or maintaining the soil organic matter levels.

Primary tillage:
- Deep tillage with subsoiler:
  Note: Subsoiling only carried out if essential to break up compaction layers.
- Manure and possibly lime spread out immediately prior to ploughing:
  - To rectify pH problems, if any.
  - To improve soil organic matter levels and nutrient levels.
  Note: Manure losnes important nitrogenous components to the atmosphere if left exposed on the surface for too long.
- Deep tillage with mouldboard or disc plough:
  - To prepare land for levelling, if required.
  - To correct unevenness through corrective ploughing, if necessary.
  - To prepare land for ridge construction.
  - To incorporate crop residues, if any.
  - To incorporate manure and nutrients.
Note: If the land is not ploughed prior to ridging the old surface can act as an impermeable layer within the ridge. This will inhibit downward infiltration of moisture when the ridge is moist and the upward movement of subsoil moisture when the ridge is dry. However, if the land was deep ploughed the previous year and is not subject to compaction problems, and if crop residues are removed, then a drag harrow can be used to break up any crusts instead of ploughing.

- Land levelling with landplane or levelling frame:
  - To prevent build up of water at low points and resultant breaching of ridges.

Note: If land initially required substantial levelling then it may be necessary to re-plough land prior to ridging, otherwise the soil may not be deep enough for ridging in some places.

- Deep tillage with ridger body and tie maker:
  - To build up ridges.
  - To tie the ridges.

Note: This operation can be classified as a secondary tillage operation.

Note: Time of tillage: The system should be installed before the start of the rains if season length is a limiting factor to yield. The initial laying out of this system requires both more time and more draught energy than the conventional tillage system, as the ridges still have to be constructed after the field has been ploughed. Hence, if draught power availability is limited, and particularly if animal draught power is being used, then it is desirable to initially lay out the system immediately after the harvest of the previous crop, as the soil is still relatively moist, which reduces the draught power requirement, the draught animals are in good condition and more time is available. Furthermore, even if all the farmer's fields are to be under this system it is desirable to introduce it one field at a time, so that the high draught power requirement to install the system is spread over several years. Note that the soil water loss during initial installation is high as both ploughing and ridging is carried out.

- Seedbed preparation:
  - Shallow tillage with ridger body and tie maker, or hand hoe:
    - To control weeds.

Note: This operation only required if weed growth has started prior to planting.

No other seedbed operations required as the two primary tillage operations should produce a sufficiently fine tilth. The timing of operations should aim at this requirement. Early rains consolidate ridge to improve seed/soil contact.

- Planting and fertilizing:
  - Planting and fertilizing:
    - Note: Planting and fertilizing is usually by hand using a hoe.
    - Note: Time of planting: Planting must not be carried out before the ridge is wet through. Rain falling on the top of the ridge soaks downwards and that falling into the furrow soaks sideways and upwards through capillary action. If insufficient rain falls a dry zone is left in the centre. If the seed is planted with the ridge in this condition and a dry spell follows, then even if the seed germinates the developing root will not grow through the dry zone and will be stunted. Furthermore, the ridge will be prone to rapid drying because the moisture in the top of the ridge is not connected to subsoil moisture and moisture will not be drawn to the top by capillary action. This will lead to poor emergence or wilting of the young plant.

    - Note: Manure and fertilizer application: The resource base of the farmer should be considered. The fertilizer should be placed 5 cm below and 5 cm laterally displaced from the seed to prevent burning. Additional manure can be placed with fertilizer.

    - Shallow tillage with ridger body and tie maker, or hand hoe.
. To control weeds.
. To rebuild ridge.

Note: Depth of tillage: Shallow so as to cut weeds just below the surface, but also depends on the amount to which the ridge has consolidated. If a hand hoe is used then it should be used so as to build up the ridge.

Note: Frequency of tillage: Adequate to control weeds.
- Some chemical weed control may supplement tillage operations.
- Some chemical pest control usually required.

Note: Control of weeds and pests during cropping season is very important so as to reduce carry over to post harvest period and next season.

YEAR 2

. Stubble or post-harvest operations:
  - Crop residues removed from field and stored for livestock:
    . To reduce soil compaction in the field and trampling of ridges by grazing livestock and to improve control of fodder supply.
    . To reduce carry over of pests in crop residues in the field.
  - Manure banded on top of old ridges immediately prior to re-ridging:
    . To concentrate organic matter in the future main plant root zone and in the future fertilizer placement zone.
  - Re-ridging carried out with a ridger body and tie maker shortly after harvest:
    . To build up the ridges.
    . To modify soil structure to conserve water.
    . To incorporate and cover organic matter.
    . To control weeds and pests.

Note: Depth of tillage: To build up to unconsolidated height requirements.

Note: Time of tillage: If the main objective of the above operations is to preserve soil water then the crop should be harvested soon after maturity and dried off-field to allow early implementation of tillage operations.

Note: If re-ridging is not carried out until just before the rains start then application of manure should also be delayed and the following operation is required:
- Shallow tillage carried out with a hand hoe, or flexible spiked-chain harrow, shortly after harvest:
  . To modify soil structure to produce a soil mulch to retain soil water.
  . To control weeds and pests.

. Primary tillage:
  Note: No primary tillage operations required for 4 to 6 years until possible structural or fertility problems occur on some soils.

. Secondary tillage:
  Note: Application of manure and re-ridging required if not carried out in the autumn, see above. Ridges and ties must be reconstructed prior to start of rains.

. Seedbed preparation:
  - Shallow tillage with ridger body and tie maker, or hand hoe:
    . To control weeds.
  
    Note: This operation only required if weed growth has started prior to planting.

. Planting and fertilizing:
  Note: As in year one.

. Crop management operations:
  Note: As in year one.

B. Characteristics of the Tillage System.

. Soil structure:
  - The soil is highly porous at the start of the season due to the ploughing and
ridging operations, and the ridges consolidate mainly due to rain action and their own weight. Due to generally low soil organic matter levels the level of soil aggregation is low and the proportion of aggregates that are water stable is low, resulting in the soil having low structural stability. However, the ridges are not subjected to compaction forces from animals or farm machinery and so compaction is not a problem. Furthermore, although the low structural stability of the soils and lack of crop residues to protect the soil surface leads to crusting, and hence low infiltration rates, the tied ridge layout holds the water on the surface until it has infiltrated. Hence the tied-ridge system compensates for the low structural stability of the soils. However, due to the lack of crop residues and the low level of water stable aggregates, capping due to raindrop action may be a problem.

Soil water:
- Infiltration: Due to the layout of the system total infiltration is very good. The reduced rate of infiltration after crusting starts is not a problem as the water is held on the surface until it infiltrates. As the ridges and ties are compacted and locally eroded into the furrows by rainfall it is necessary to reconstruct them at regular intervals, especially at the start of the season when soil protection by crop cover is low. This operation is combined with weed control. Soil crusts are also broken during this operation.
- Water holding capacity: This is good at the start of the rains due to high porosity down to full plough depth. Due to the low structural stability of the soil and low soil organic matter content it gradually declines as the season progresses as well as in subsequent years when ploughing is not included. However, as the soil under the ridge is not compacted by tillage traffic, the porosity remains acceptable resulting in an acceptable water holding capacity. The addition of organic matter in the form of manure is very important as a means of increasing the water holding capacity, especially of sandy soils.
- Drainage: This system has excellent drainage attributes. If waterlogging becomes a problem the ties can be broken, starting from the bottom up, to promote drainage and ensure that the top of the ridge is well drained.
- Evaporation:
  - Full depth ploughing and ridging in the first year and the resultant porosity of the soil results in almost all the soil water to plough depth being lost. This is particularly true if these operations are carried out at the end of the season and prior to a long dry spell. However, it is generally better to correctly implement the system when draught power is available at the end of the season, and to tolerate the loss of soil water in the first year and the resultant late start to the season.
  - Ridging increases the surface area of the soil exposed to evaporation resulting in higher evaporation than from a flat surface. Temperatures in the ridge are also higher than would occur on the flat thus further increasing evaporative losses from the ridge.
  - Shallow tillage to break the capillary continuity between the surface and lower layers, and to provide a dust mulch is the most effective means of reducing evaporation from the subsoil over long dry periods. In this tillage system this is carried out during the season, mainly during weeding and re-ridging operations, and especially immediately after harvest in arid areas.
- Erosion potential:
  - The erosion potential of this system is very low provided the system is correctly designed and laid out. This is because runoff is minimised and even when it does occur it does so down the gentle slope of the furrow, which slows its speed and hence its erosive potential.
- Soil organic matter:
  - As crop residues are not retained in this system, other than possibly in the first
year, soil organic matter levels are low. However, as primary tillage is only undertaken in the first year and all other tillage is shallow, loss of soil organic matter due to tillage is low. Hence, soil organic matter levels in this system are higher than in a conventional tillage system without the annual return of crop residues. The use of manures and composts to raise soil organic matter levels in this system is important.

Nutrient requirements:
- Nutrients are not available from the decomposition of crop residues and so for sustainable production all required nutrients have to be added in the form of manures and fertilizers. There are two main advantages that the system has over others, firstly; few nutrients are lost through erosion and, secondly; following excess rain the main path of water draining through the soil is from the furrow downwards and, as the manures and fertilizers are placed in the centre of the ridge and roughly halfway between the top of the ridge and the furrow, there should be very little leaching of these nutrients. However, apparently no tests have been conducted to validate this, which is surprising seeing that the leaching of fertilizers is a serious problem, particularly on well drained sandy soils.

Seed germination and emergence:
- The ridge must be wet through prior to planting, otherwise seed germination and emergence and early plant growth can be poor, especially in arid areas. This may result in slightly delayed planting, especially in the first year, compared to other tillage systems and hence shorten the available growing season. The higher temperatures in the ridge and the higher drying rate of the ridge as opposed to the flat may, under arid conditions, result in lower germination and emergence rates, particularly on sandy soils. Once the plants are established this aspect is counterbalanced by the very good infiltration characteristics of the system, however the final balance is determined by the characteristics of the rainfall season. The inclusion of manure or compost, which have high water holding capacities, near the root zone of the young plant is important in overcoming this disadvantage of the system, together with the use of shallow tillage to reduce evaporation losses. The lack of crop residue cover encourages capping problems and this can inhibit good emergence. However, this problem can be overcome using hand rakes prior to emergence.

Weeds:
- Good weed control is an important positive attribute of this system, similar to conventional tillage system.

Pests and Diseases:
- Good pest and disease control is an important positive attribute of this system, similar to conventional tillage system.

Harvesting:
- The ridges and lack of crop residues facilitates harvesting of crops with a low stature.

Energy inputs and power requirements:
- The energy inputs are high in the first year due to the high energy requiring ploughing and ridging operations. From the second year onwards only re-ridging operations are required, and over roughly four years the total draught energy input is roughly half that of the conventional tillage system over the same period.

Equipment requirements:
- A wide range of equipment is generally available. However, in countries where ridging is not commonly carried out using animal draught, suitable ridger bodies are frequently not available. To minimise draught and minimise soil disturbance, and to effectively weed the ridge during re-ridging operations, only appropriate ridger bodies should be used. These are described in Section 5. Ploughs can also be used to build up the ridges, however these require two passes, where a
The ridger body only requires one, and soil disturbance when using ploughs is also excessive.

Economic characteristics:

- Profitability:
  - Input costs: The costs of implementing the tillage operations are high in the first year of installing the ridges. Over a four year period they should be roughly half those of a conventional tillage system. Costs of weed, pest and disease control is similar to those of conventional tillage systems. Fertilizer costs should be lower than those in conventional tillage systems due to lower leaching of fertilizers and lower losses due to erosion.
  - Yield: Dry hot climatic conditions at the start of the season are likely to suppress yields, especially on sandy soils with a low water holding capacity. Good yield under excess rainfall as not prone to water logging problems.

- Risk: Highly adaptable system to high or low rainfall because it can be used to avoid water logging problems and to conserve water. However, if dry and hot conditions at the start of the season are likely and if on sandy soils with low water content then risks of low yield are high.

Further details of the above points can be obtained from the relevant sections in Section 2.

A large range of reduced tillage systems have been developed to reduce various inputs and to adapt the systems to local conditions. These systems are covered in detail in various research papers and farming magazines. In addition to these sources one of the best ways of looking at the alternatives is to study the range of systems that successful farmers use.

3.1.3. Conservation Tillage Systems

These are tillage systems where the number of tillage operations are minimised to reduce energy requirements and to reduce soil disturbance, and where the crop residues are left on the surface to aid soil and water conservation. Alternative names used are minimum tillage, trash farming, crop residue farming, crop mulch farming. Generally at least 30% of the soil surface should be covered with crop residues for the system to classify as a conservation tillage system. Primary tillage operations are usually, but not always, excluded. The most extreme form of this system is no-till or zero-till, in which no tillage is undertaken and the only soil disturbance is during the placement of seeds and fertilizers, and where herbicides are used for weed control.

The crop residues should cover more than 30% of the soil surface for them to be effective in the conservation of soil and water, as was discussed in Section 2.2.1.3 and this requirement is difficult to meet in many regions for the following reasons: Firstly, in many arid regions the amount of vegetative production is low and even if all crop residues are left on the surface they will not cover the 30% requirement. In these regions reduced tillage systems are more appropriate than conservation tillage systems, as tillage operations are required to supplement the conservation benefits of the limited surface mulch. For example, strip catchment tillage and pot-holing, etc., can be used, as discussed in the previous section. Furthermore, local climatic conditions may determine that less than 30% cover is acceptable without additional operations. Secondly, crop residues are frequently used as supplementary fodder for animals, and several possible approaches can be used to try to overcome this restraint as discussed in Section 2.6.2.

High levels of crop residues can be left on the surface even though primary tillage operations are carried out, e.g., subsoiling with a ripper tine, chisel ploughing and para-
ploughing. Even a light discing operation can leave a substantial proportion of the crop residues remaining on the surface. The border between reduced tillage and conservation tillage systems is blurred. For example, a tillage system involving ripping and light discing but leaving more than 30% of the surface still covered with residues would generally be classified as a reduced tillage system, because of the still substantial amount of energy input and soil disturbance involved even though the surface cover requirements are met for a conservation tillage system. The proportion of crop residues buried by different tillage operations was given in Section 2.2.1.3. Care should be taken not to confuse the proportion of the original amount of residues remaining on the surface after carrying out an operation, with the proportion of the soil surface covered by crop residues.

Only one conservation tillage operation will be described in detail and that will be the zero-till system. Strictly speaking, as soon as deep fertilizer or seed placement is undertaken then the system can no longer be called zero-till, and this also applies to mechanical weeding. Under these limitations the only system that would qualify would involve the broadcasting of seeds and fertilizer and the use of herbicides for weed control. However, this reservation will be ignored here. Implementation of the system using both draught implements and hand implements will be covered. The use of herbicides and the use of the hand hoe to control weeds will also be covered.

3.1.3.1. Zero-Till

This system involves the retention of all crop residues on the surface and these should cover more than 30% of the surface area. Soil disturbance is limited to the placement of seed and fertilizer, as well as mechanical weeding for those farmers without access to herbicides, or for whom the use of herbicides is not within their economic interests. This system has very good soil, nutrient and water conservation characteristics, and results in high levels of soil organic matter when used over a long period of time and hence good soil structural characteristics. It also minimises draught energy input. However, there are several drawbacks to the system.

The main drawbacks of the system are the weed and pest problems resulting from the retention of crop residues and the lack of soil inversion. Good management and the use of herbicides and pesticides can overcome these. All three of these requirements impose their own severe limitations on the adoption of the system. Good management can be promoted by effective extension work and by ensuring that farmers adopt the system initially on only a small area of land so that initial implementation errors can be rectified. Herbicides can provide a labour and cost efficient means of controlling weeds for resource rich farmers, if they are available. If they are not available or not appropriate then on small areas of land, or where there are no labour shortages then on larger areas of land, mechanical weeding by hand can be carried out. Pesticides are generally required. Due to the financial, human and environmental cost of the use of many farm chemicals there has been an increasing interest in the use of organic farming methods that exclude chemical use. Many of these methods are still in the experimental stage but must be treated seriously, as it appears likely that they can substantially cut the cost of production and so improve the financial and nutritional status of the farming household, as well as protect the consumer and the environment.

The implementation, objectives of the operations and the characteristics of the system are listed below. Where the operations and objectives are similar to those in the previously described conventional tillage system, the detailed objectives and notes will not be repeated, and hence these should be referred to for completeness.

A. Implementation, objectives of operations and notes:

YEAR 1
Note: The conventional tillage system should be implemented in the first year of this system as it is very important that prior to implementing the zero-till system that all soil, weed and pest problems are overcome or minimised. This is for the simple reason that once the zero-till sequence has been started then tillage is no longer available as a means of intervention to resolve problems, unless the zero-till system is interrupted. In order to achieve this the following steps should ideally be implemented during the first year of the conventional tillage system:

- Correct any uneven soil surface resulting from faulty ploughing in the past or inherent unevenness, which would result in an uneven distribution of water over the field. Use corrective ploughing measures, damscoops or land-planes.
- Correct any compaction problems which would restrict root growth or infiltration.
- Incorporate crop residues, manures, lime and fertilizers to improve soil organic matter levels, to correct pH levels and to improve nutrient levels, respectively.
- Control weeds through full inversion ploughing and good weed control throughout year.
- Control pests through good control throughout year.
- Planting rows should be slightly off-contour, parallel to the contour ridges.
- The conventional tillage system may need to be reverted to occasionally to correct pH problems through incorporating lime, to correct compaction problems on high density soils, and to control weeds and pests. If this is done not all the accumulated benefits of the zero-till system to the soil will be lost.
- Fields should be fenced off or arrangements made to keep livestock out of the fields after harvest.

YEAR 2

- Stubble or post-harvest operations:
  - Treat crop residues:
    - To control some pests by exposure to sunlight and predation, e.g. knock over maize stalks including base to control stalkborer in maize.
  - Pest control with pesticide:
    - To control carry over of pests to next crop.
  - Weed control with herbicide:
    - To control weeds in order to reduce carry over to next crop, and to reduce evapotranspiration to conserve soil water.
    - To remove food supply and habitat for certain pests.
  - Very shallow inter-row and within-row tillage with hand hoe shortly after harvest:
    - To modify soil structure and retain soil water.
    - To control weeds.

Note: Usually only carried out if no herbicides available or if they are not cost effective. However, shallow tillage is the most effective way to control soil water evaporation by creating a dust mulch over a long dry period.

- Primary tillage:
  Note: No primary tillage carried out.

- Seedbed preparation:
  Note: Seedbed preparation not carried out.
  Note: Weed control immediately prior to planting is important. This is carried out using a hand hoe if herbicides are not being used.

- Planting and fertilizing:
  - Planting and fertilizing with animal or tractor drawn equipment slightly off contour:
    Note: Planting and fertilizing is into the old inter-row line so that the old planting line with crop stems and roots are left intact and binding the soil, to further reduce erosion and enhance soil and nutrient conservation. As the planting and fertilizing furrow is slightly off-contour this also acts as a strip tillage catchment.
system with increased infiltration occurring along the planting line, as in the rip-on-row system.

- Note: Farmers intending to hand plant and fertilize may also open the planting row with an animal drawn ripper tine. This also increases infiltration along the planting line as described above and turns the system into a strip tillage catchment system.

- Planting and fertilizing and possibly adding humus, using hand hoe direct into planting holes:
  - To improve the seed/soil contact, as seedbed preparation not previously undertaken, hoe should be used to produce fine tilth in planting hole, and manure/decomposed organic matter added beneath seed level.

Note: Also hand plant into old inter-row line to enhance soil and nutrient conservation for the reasons given above.

Note: Fertilizer placement and use: As in conventional tillage systems.

- Crop management operations:
  - Herbicide application:
    - To control weeds.
  - Shallow tillage with hand hoe (if no herbicides used):
    - To control weeds.
  - Pesticide application:
    - To control pests.

Note: Well managed, timely weed and pest control is extremely important in this system, as these problems can easily get out of hand without tillage to resort to. Control of weeds and pests during the cropping season is also very important so as to reduce the carry over to the post harvest period and next season. If weeds are controlled effectively with this system at the start then they become less of a problem in subsequent years, as most of the viable seeds near the surface would have germinated and been destroyed and dormant seeds are not continually been brought up to the surface through tillage.

B. Characteristics of the Tillage System.

- Soil structure:
  - Soil structure is gradually improved due to the build up of soil organic matter in this system, which in turn leads to higher aggregation and in particular to an increased proportion of water stable aggregates, and increased porosity. Amongst the benefits of improved soil structure are lower levels of soil compaction caused when machinery passes over the surface. The range of soil moisture contents over which it is possible to take machinery into the field without causing compaction problems is also increased, which adds flexibility to the farmer's operations.
  - The improved soil structure and protection of the soil surface by crop residues from raindrop impact removes the possibility of crusting problems.

- Soil water:
  - Infiltration: This is good due to the high porosity resulting from good soil structure and the protection of the surface by the crop residues from raindrop impact.
  - Water holding capacity: This is good due to the high porosity and high soil organic matter content. This results in a higher availability of water to the crop for a given precipitation. Combined with the low evaporative losses, described below, this system is highly appropriate for use in arid areas prone to short-term droughts.
  - Evaporation: Loss of water due to evaporation is low due to two main factors: Firstly, the soil surface is protected by the crop residues. Secondly, the lack of tillage operations and especially deep tillage bringing the moist soil up to the surface where the moisture can rapidly evaporate. However, over very long dry periods soil water evaporation is better controlled by shallow tillage than crop
residues, as the former breaks the capillary continuity between the surface and the deeper layers. On small lands the hand hoe can be used to achieve this, especially over the dry season.

- Drainage: Surface runoff from this system is low and on poorly drained soils this can lead to waterlogging problems. This system should not be used where these problems are likely to occur.

- Erosion potential:
  - The erosion potential of this system is very low and is one of the main reasons why it is used. This is due to several reasons, firstly; infiltration is high and remains high during a rainstorm due to good soil structure and a protected surface, secondly; the water holding capacity is high, thirdly; the runoff is low and, fourthly; when runoff does occur it is slow because of the roughness due to the crop residues on the surface.

- Soil organic matter:
  - The soil organic matter characteristics of this system are the best of all tillage systems. The levels of soil organic matter are gradually built up under this system because its rate of decomposition is low, due to the lack of tillage, and all crop residues are retained and these gradually decompose into soil organic matter. High levels of soil organic matter lead to good soil structure and resistance to compaction, high infiltration rates, high water holding capacity, low erosion potential and good nutritional characteristics.

- Nutrient requirements:
  - In conservation systems additional nitrogen based fertilizer is required, compared to conventional systems with the return of crop residues, because of the slow decomposition of soil organic matter and the associated reduced release of nitrogen. Over time the quantity of some other fertilizers used may be reduced as the fertility and soil organic matter content of the topsoil increases, see section on conventional tillage system. On sandy soils the improved levels of soil organic matter with this system hold the nutrients in the soil and reduce leaching problems.

- Seed germination and emergence:
  - Seed germination and emergence with this system is fairly variable depending on a number of factors. The seed/soil contact in this system is generally poor due to the lack of seedbed preparation. However, this may be compensated for by the higher moisture content of the soil surface due to the crop residues. The protection of the surface by the crop residues and the good soil structure substantially reduces capping problems and aids emergence. Soil moisture levels at the start of the season are good compared to other systems, because moisture is not lost through tillage, and the water infiltration and retention characteristics of the system are good. This allows an early start to the season and also aids good germination and emergence.

- Weeds:
  - A major drawback of this system is the high potential for weed infestation due to the lack of weed control through primary and secondary tillage operations. The presence of large quantities of crop residues on the surface generally precludes the use of animal or tractor drawn weeding implements. The use of herbicides together with good management can fully overcome this problem and, for resource-rich farmers, can do so in a more cost effective way than the use of tillage. For resource-poor farmers, or for those without access to herbicides, weeding using the hand hoe can be carried out. This is highly labour intensive but may not be substantially more so than on the conventional tillage system using hand weeding, especially after the first couple of years as dormant seeds from lower soil layers are not brought up by deep tillage. The control of weeds before they become established is very important. This usually means destroying the weeds before they reach 5 cm in height. Good planning and management is the key to good weed control in this system.
Pests and diseases:
- Another major drawback of this system is difficult pest and disease control, as these are carried over in the crop residues retained on the surface. The use of pesticides is generally required with this system although organic farming methods are being developed to reduce the requirement for pesticides. For some species of pests knocking down or chopping up crop residues can destroy pests. Good control of the pest and diseases in the previous year and in between crops is essential if infestation is to be avoided. Good weed control in between crops removes the food supply and habitat of some species for large proportions of the year and this limits pest infestation levels. Revision to conventional tillage systems may be essential to adequately control pests and diseases occasionally. Again, good planning and management is the key to the control of pests in this system.

Harvesting:
- The presence crop residues may interfere with the harvesting of crops with a low stature.

Energy inputs and power requirements:
- The total energy inputs of this system over several seasons are very low and this is a major advantage of this system. The power requirements for all operations are generally low.

Equipment requirements:
- The presence of crop residues on the soil surface interferes with all tillage operations and generally specialised equipment is required. This particularly applies to planting and fertilizing equipment. However, many farmers have made simple modifications to standard equipment and these have been found to be adequate. Generally, the use of animal or tractor drawn weeding implements is not practical because of the presence of crop residues on the surface, and this particularly applies when there is a young crop in the field. A wide range of applicators for herbicides and pesticides, both hand operated and tractor mounted, are available.

Economic characteristics:
- Profitability:
  - Input costs: Generally, the costs implementing the system are lower than for conventional tillage systems as there are no costs for tillage operations. However, costs of weed, pest and disease control are higher than those of conventional tillage systems. Fertilizer costs should be lower than those in conventional tillage systems due to lower leaching of fertilizers and lower losses due to erosion. However, the cost of nitrogen based fertilizers are slightly higher.
  - Yield: In dry hot climatic conditions this system should provide the highest yields. Under conditions of excess rainfall waterlogging problems may suppress yield.
- Risk: Main risk is from weed, pest and disease levels getting out of control. In regions where excess rainfall is likely the suppression of yield due to waterlogging is also a risk.

Further details of the above points can be obtained from the relevant sections in Section 2.

Conservation tillage systems, and especially zero-till, have only relatively recently been developed in response to concern to improve soil, nutrient and water conservation and to reduce energy inputs, and so improve the sustainability and profitability of crop production. Furthermore, they have been developed primarily with the resource-rich farmer in mind. As these systems have so much potential for the resource-poor farmers, but also have serious disadvantages, e.g. weed, pest and disease control, a lot of research is being carried out to overcome these disadvantages using farming systems that are less chemically based in order
to reduce financial and environmental risk. It is therefore important that extension organisations keep up to date with the latest research findings in this field.

3.2. CULTIVATION AND MANAGEMENT SYSTEMS

As outlined at the start of this section the terms cultivation and management systems are often used interchangeably and basically cover all aspects of crop production systems, including tillage systems. Cultivation and management systems frequently determine which tillage system can be used, for example, by imposing time limitations on the preparation of the field in serial cropping systems, or spacial limitations because of the presence of another crop in the field in strip cropping systems. The various management systems are also used to complement the main attributes, or compensate for the main deficiencies, of the tillage system being used, and visa versa. For example, in a tillage system that has high erosion potential, a strip cropping system that includes a crop with close in-row spacing can be used to improve the resistance to runoff and hence improve the erosion protection of the whole system. The use of crop rotations is an ideal way to improve fertility and pest control in most tillage systems. It is very important that crop production is viewed as a coherent system, with all the component parts, including tillage, having key attributes that are complementary and appropriate to the region, farm and farmer using them. Unger (1984) discusses crop cultivation and management systems in relation to tillage systems in detail, and includes numerous examples and references, and for this reason only a brief overview of the subject, based on Unger's report, will be given here.

3.2.1. Cultivation Systems

The two cultivation systems that will be discussed here are the traditional shifting cultivation system and the continuous cultivation system, including managed fallow. The means of implementation of the cultivation and tillage systems will be covered in Section 5, including the various energy sources used.

3.2.1.1. Traditional Shifting Cultivation

Shifting cultivation is widely practised in Africa, South and Central America, South East Asia and Oceania. The area of land used for shifting agriculture is estimated by various authorities to range from 3.6 to 8 billion hectares, and to feed 8% of the world’s population.

In this system a field is cleared of its natural vegetation, usually through slashing and burning, and then cropped for two to three years, before being abandoned. The initial fertility of the soil is increased by the incorporation of the ash and plant residues into the soil, and weed seeds are destroyed by the fire. After two to five years the fertility of the soil is exhausted, as no additional nutrients are usually applied, and weed infestations starts to build up. The field is then abandoned and the natural vegetation allowed to regenerate and the fertility of the soil to build up. After 15 to 20 years when soil fertility has been restored to its natural state the field is again cleared and then cropped for a few years.

In suitable ecosystems this system is environmentally acceptable, as it allows the natural ecosystem to regenerate, providing the following conditions are met: Firstly; the soil and vegetation should be allowed to fully regenerate prior to the cropping cycle starting again and, secondly; only a small proportion of the land in a particular area should be cropped at any one time. This latter condition ensures that the natural flora and fauna can recolonise the abandoned cropped area. In some ecosystems, such as rainforests, where a high proportion of the nutrients are held within the growing and decaying vegetation and the soils are very poor due to leaching from the high precipitation, severe problems in regeneration occur unless only
very small areas are cropped at a time. Once population pressure starts to build up, neither of the two conditions for environmental acceptability can be met, even in suitable ecosystems. Shifting cultivation then becomes highly destructive to the environment, and crop production from this system is then not sustainable.

The advantages of the system are the low capital cost involved and the low running costs, as the soil is initially naturally fertile and this fertility is increased due to the incorporation of the ash and plant residues in the first year, and weed and pest problems are also low for the first year. The land is generally cleared with axes, machetes, fire and hoes. The use of fire saves labour, leads to a flush of soil fertility in the first year and also kills weed seeds. The farming household generally provides all the labour inputs.

The disadvantages of the system, when implemented in balance with the environment, include the large land area requirement, the high labour input required when clearing a new plot, the limited opportunity for mechanisation and the frequent need to relocate the dwelling. When the system is implemented out of balance with the environment then its potential for severe land degradation, especially due to erosion, is very high.

With increasing population pressure there is the incentive to decrease the period that the old plot is left to regenerate and to increase the period over which a particular plot is cropped. The first objective can be achieved to some extent in an environmentally acceptable way by not completely destroying all the trees in the cropped area. This practice was carried out in Zambia and Zimbabwe where the trees within the plot were only cut down to breast height, and the fires were not built around the tree stumps as is commonly done when clearing a plot. This practice allowed the natural vegetation to regenerate rapidly and so protect the soil from erosion and promote the build up of soil organic matter, and this reduced the period between cropping the same piece of land to around ten years. The second objective of increasing the length of time that a plot can be cropped economically can be achieved by the use of fertilizers and manures, and crop rotations and multiple cropping systems to protect the soil from erosion and maintain fertility. As this period increases the system moves towards the continuous cultivation system.

3.2.1.2. Continuous Cultivation

In continuous cultivation systems the land is cultivated annually, although fallow periods of one or two years may be used occasionally. This contrasts with shifting cultivation systems in which land is fallowed for a much longer period than it is cultivated. Continuous cropping at subsistence level replaces shifting cultivation systems when available land resources have been completely utilised due to increasing population pressures, as described in the previous section.

With continuous cultivation systems it is very important that the soil is properly managed to maintain good soil structural and fertility characteristics. Unless this is done severe or irreversible land degradation will occur and yields will decrease resulting in unsustainable crop production and possible abandonment of the land. Under subsistence level farming this frequently occurs and it is very important that improved practices are introduced and adopted. This applies equally to farmers operating above the subsistence level, as the surplus food they provide feeds the rest of the population of the country. As discussed in the previous section this involves the use of improved tillage, cultivation and management systems as well as the development of improved infrastructural support and a supportive social and political environment.

The managed fallow system is classified within the continuous cultivation system, but is similar to the shifting cultivation system in that a plot is cropped for a period and then left fallow for another period to achieve certain objectives. The difference is that the plot is managed, i.e.
cultivated to achieve the objectives rather than left to natural regeneration and the fallow period usually only lasts one to two years. The objectives of leaving the land fallow may be to build up the water content of the soil, to increase soil organic matter and increase fertility, to restore soil structure, to control weeds, pests and diseases, etc. Some examples of these are given below.

In very arid areas plots may be left fallow during one rainy season to build up moisture reserves and only cropped the following rainy season. Alternatively, in some regions and for some crops such as winter wheat, the land may be left fallow during the hot rainy season to build up moisture reserves and then cropped during the cooler dry season with no additional water being supplied. In managed fallow systems such as these the soil surface is cultivated to maximise infiltration and to minimise evaporation and evapotranspiration losses. If crop residues are not retained on the surface to assist this process then shallow tillage operations are usually required after each significant rainfall. These are required to roughen the surface, to facilitate infiltration and to reduce the erosion hazard due to either water or wind, and to break the capillary continuity between the surface and the deeper layers. The latter objective is particularly important when reducing evaporation over a long dry spell. These aspects were discussed in Section 2.1.2.4. A disadvantage of the frequent tillage operations is that it promotes the decomposition of soil organic matter and it also requires a substantial energy input. The practice of using herbicides to control the weeds, without the retention of crop residues on the surface and with no tillage to reduce the erosion potential, has resulted in severe erosion problems.

For some crops prone to particular pests, for example tobacco and nematodes, a common practice is to rotate the prime crop with a fallow crop that is highly resistant to them. For example, in Zimbabwe tobacco is frequently rotated with Katambora Rhodes Grass (Chloris gayana) which is highly resistant to root-knot nematodes (Meloidogyne spp.), and hence is not a food source or habitat for them, and thus the nematode populations decline rapidly. After a year the grass is ploughed under and this also improves the organic matter content of the soil and hence its structural and nutritional characteristics.

3.2.2. Management Systems

Those facets of management systems dealing with the agronomic aspects of crop production, such as planting; fertilizer application; weed, pest and disease control; etc., were discussed in Section 2.4. This section will briefly cover some other important aspects of management systems, namely; continuous cropping, crop rotations and multiple cropping.

3.2.2.1. Continuous Cropping

Continuous cropping, as opposed to continuous cultivation, involves the production of the same crop on the same plot of land each year. This applies both to crops that are planted and harvested within the year, as well as to crops that take longer than one year to mature. Although the emphasis is on the same crop each year, this does not preclude the use of a cover crop, provided the main crop is still grown during the appropriate growing season.

The major advantage of continuous cropping is the potential for obtaining the greatest production of the most desirable crops. In any particular location, one or a few crops are usually most desirable because of yield levels, ease of production, available markets, farmer preferences, etc. Consequently, the largest possible area is devoted to the crop that enhances the potential for the greatest yields or economic returns to the producer. However, this strategy also has the potential for the greatest loss due to bad weather conditions or pest infestations, etc.

Where production is limited to the same crop or to crops requiring the same equipment
then another advantage of continuous cropping is the relatively low capital expenditure on equipment required. The amount of management expertise to efficiently implement a continuous cropping system is also generally less than that required for systems involving more than one crop, either in rotations or when grown on separate areas.

The influence of continuous cultivation on soil and water conservation is related to the type of crop grown. Generally, continuous production of high-residue crops aids soil and water conservation, whereas continuous production of low-residue crops is detrimental to soil and water conservation. As Unger (1984) reports, the continuous production of small grains can be one of the most effective soil and water conservation practices, especially when the crop is growing during the period of maximum erosion potential and when residue-based tillage practices are used. However, the weed, pest and fertility problems associated with this system must be taken into account when determining the sustainability of the system.

Continuous cropping tends to favour certain weeds that have similar growth periods to the crop and this allows their build up over successive years. Furthermore, if herbicides are the main means of weed control then continuous cropping limits the range of herbicides that can be used. For example, if a grain crop is being grown then the range of herbicides that can be used on the grass weeds is limited, as the grain crops and grasses both belong to the graminacea family. Continuous cropping also favours the pests associated with that crop, because their life cycle is generally adapted to the crop, or an associated species, and the crop is provided for them each year. Soil fertility may also become a problem with continuous cropping as the same crop extracts the same nutrients from the same depth year after year. Furthermore, the crop residues of some crops may have low nutrient value once they have decomposed.

### 3.2.2.2. Crop Rotations

There are two general types of crop rotations. The first is the shifting cultivation type in which an area is intensively cultivated for a few years and is then abandoned or fallowed for a longer period to restore soil fertility. This type has already been discussed and will not be discussed further. The second type involves the growing of one or more crops alternately with a fallow period, or the growing of more than one crop in a cycle over successive seasons, on the same plot of land. As the use of the fallow has also already been discussed under continuous cultivation systems only the latter will be discussed. Unger (1984) overviews this subject in more detail than will be given here.

Crop rotations may be a simple alternation between two crops in successive years, for example, cotton alternating with sorghum, or more complex where several crops are grown requiring four or more years for completion of the cycle, for example, maize, maize, groundnuts, sorghum. The rationale for the selection of specific crops involved in a rotation and the order in which they are grown is based on a number of objectives, including:

- To produce desired crops.
- To reduce the risk of total crop failure.
- To facilitate the implementation of the tillage and cultivation operations involved.
- To even the distribution of expenditure, food supply and farm income over the year or longer term.
- To control weeds, pests and diseases.
- To control soil organic matter and fertility levels.
- To control soil and water conservation.
- To improve the use of available water and nutrients.

Furthermore, on any one farm using a specific rotation, different plots of land are generally under a different cycle of the rotation at any one time. The reasons for this are the same as the first four objectives given above. These objectives will be discussed in the order
As discussed in the previous section the greatest economic returns would be achieved if the most desirable crop could be grown continuously. However, because of the risk involved, or because of fertility, weed, pest, disease, water, soil erosion, or other limitations associated with continuous cropping, it may not be possible. It then becomes necessary to break up the continuous cropping system by the introduction of one or more crops that are desirable in their own right and that also complement the most desirable crop by overcoming some of the limitations listed above.

For subsistence farmers the assurance of an adequate food supply for the household is the most important criteria used in the selection of the crops to be grown. In order to meet this criterion complementary crops that meet the household’s nutritional requirements are grown, for example, a cereal crop for carbohydrates, a pulse crop for protein and vegetables for other nutrients. Furthermore, they need to minimise the risk of total crop failure and it is therefore necessary to have more than one crop growing at a time. These crops should ideally also have sufficiently different characteristics that they are not equally vulnerable to water shortages, and the same pest infestations, etc. To meet these requirements it would be possible to use continuous cropping systems, but to have different plots on a farm being continuously cropped under different crops. However, to overcome the fertility limitations, pest and disease build up problems, etc., it is necessary to have crop rotations and to ensure that different plots on the farm are under a different crop in the rotation.

The latter arrangement also facilitates the implementation of tillage and cultivation operations. For example, in a one-crop system only a limited area on a farm can be planted at the optimum time due to limited labour or equipment resources. This would result in lower overall yields in a region where yields are limited by season length. By using a multi-crop system, and using crops with different planting or harvesting dates, or which require various tillage or other cultivation operations to be carried out at different times, these operations can be carried out in a more timely manner because a smaller area is devoted to any given crop. A multi-crop arrangement can be met by either having different plots on a farm being continuously cropped under different crops, or by having different plots on the farm under a different crop in a rotation.

A multi-crop arrangement also meets the requirement of evening the distribution of expenditure, food supply and farm income over the year or longer term. By having different crops with different planting dates, etc., the labour requirements can be spread more evenly. If hired or bartered labour is being used to supplement the permanent labour force then these costs can be reduced. The draught power requirements for tillage can also be spread more evenly and this can reduce the amount of draught power sources or equipment required, and so reduce capital costs. By having different crops harvested in the same year, and ideally at different times of the year, complementary food crops or a food and cash crop can be harvested in the same year, so evening food supply and farm income. By evening out the supply of food the storage costs can be reduced, the foods nutritional value may be increased and the risk of total crop failure reduced.

Crop rotations are a very important component of any comprehensive programme to control weeds, pests and diseases. This is particularly true in conservation tillage systems where crop residues are retained on the surface in the following crop and so facilitate the carry over of pests and diseases. It is then highly desirable that the crop planted into the residue is not susceptible to the same pests and diseases as the previous crop. Although this can never be fully achieved the overlap of their susceptibility to the same pests and diseases should be minimised. With regard to weed problems, alternating the crops between monocotyledons and dicotyledons allows herbicides to be used that target weeds that belong to the opposite group type in the successive rotations and so prevent a build up of weed problems. As pointed out previously, continuous cropping tends to favour certain weeds that have similar growth periods.
to the crop that allows their build up over successive years, and this can be overcome by rotating crops with different growth periods. The effects of different tillage operations and systems on weed, pest and disease control were covered in Section 3.1.

Crop rotations are also used to increase soil organic matter and fertility levels. For a given tillage system and given climatic conditions, the soil organic matter levels are primarily determined by the amounts of crop residues left on the surface or incorporated into the soil. If the most desirable crop has low residue levels then it can be alternated with another desirable crop that has high residue levels so as to increase or maintain soil organic matter levels. This is relevant to both conventional and conservation tillage systems provided residues are incorporated in the former. Crop residues not only have a beneficial effect on the soil physical conditions, they also benefit the soil chemical conditions by releasing nutrients when they decompose which are then available for use by a growing crop. Legumes provide more nitrogen than non-legumes when they decay, and it is particularly important that they are used in rotations in regions where nitrogen based fertilizers are expensive or in short supply, or by subsistence farmers who do not apply additional fertilizers. The dynamics and control of soil organic matter was dealt with in detail in Section 2.1.3.

The effect of crop rotations on potential soil loss due to water erosion, as determined by the Universal Soil Loss Equation, is illustrated by the crop management factor C. This was discussed in Section 2.2.1.2. In all cases where a high-residue crop is included in a rotation, the potential for soil loss is lower than where the low-residue crop is grown continuously. Crop management practices that affect the C values include tillage, crop rotations and residue management practices. When the potential for erosion at a given location cannot be reduced to acceptable levels by crop management, then other supporting practices should be used to control erosion. These were discussed in Section 2.2.1.3. The control of wind erosion using residues and supporting practices was discussed in Section 2.2.2.3.

There are several characteristics of a crop that contribute to its influence on soil erosion potential. These can be divided into two, namely, the protection that the crop residues afford the soil, and the protection that the growing crop affords the soil. The crop residues reduce soil and nutrient loss by, firstly; protecting the soil surface when retained on the surface as a mulch in a conservation tillage system, and secondly; the decomposed residues protect the soil from erosion by improving the soil structure and reducing runoff. This second result is achieved by an increase in the level of soil organic matter and hence the number of water stable aggregates in the soil, which in turn reduces the dispersion of soil particles due to the breakup of soil aggregates on the surface from raindrop impact, which increases water infiltration and reduces runoff. With regard to the protection afforded to the soil surface by the growing crop several characteristics need to be considered. Firstly, the growing period and time of planting of the specific crop determines whether leaf cover to reduce the impact of the raindrops on the soil surface is provided during periods of high erosion potential. Secondly, the amount of cover that the crop gives is determined by planting density, the amount of vegetative growth and the habit of the plant, i.e. the relative sizes of the leaves and stems. Thirdly, the amount of resistance to horizontal runoff that the crop provides is determined by plant spacing and the size of the stems.

Each of the above characteristics depends on the crop species. When the most desirable crop has poor characteristics with regard to soil protection then it can be rotated with a crop that has good soil protection characteristics. On badly degraded soils, ideally only crops with good soil protection characteristics should be grown until the condition of the soil has been improved. The control of soil erosion was covered in detail in Section 2.2 and this section included a list of crops producing high and low quantities of residues. It needs to be emphasised that in an arid region a high-residue producing crop which is not drought resistant may easily produce less cover while it is growing and less residue after harvest than a low-residue but drought resistant crop.
The last two objectives discussed aim to improve soil organic matter levels, and hence improve soil structure and increase the number of water stable aggregates present, and also reduce erosion and soil and nutrient loss by reducing runoff. If these objectives are met by a crop rotation then they also result in increasing the water and nutrients available to the crop and hence increase its potential yield. Different crops also have different rooting depths and hence extract water from different depths. They also extract different nutrients and return different nutrients with their residues. Hence, the use of crop rotations results in a fuller use of the available water and nutrient resources of the soil than continuous cropping.

3.2.2.3. Multiple Cropping

Multiple cropping is the intensification of cropping in terms of time and space. It involves growing two or more crops on the same field in a year. This contrasts with the crop rotation systems described in the previous section, in which only one crop was grown in a field in a year and a different crop was then grown in the same field in the succeeding year. There are two types of multiple cropping systems, namely, sequential cropping and intercropping and these are divided into subsystems. The definitions below are those given by Andrews and Kassam (1976) as given in Unger (1984):

- **Sequential Cropping:** Growing two or more crops in sequence on the same field per year. The succeeding crop is planted after the preceding crop has been harvested. Crop intensification is only in the time dimension. There is no intercrop competition. Farmers manage only one crop at a time in the same field. (Note: The farming year is 12 months except in arid areas where only one crop can be grown every 2 years due to water limitations. In these areas, sequential cropping involves growing two or more crops every 2 years).
  - Double cropping: Growing 2 crops a year in sequence.
  - Triple cropping: Growing 3 crops a year in sequence.
  - Quadruple cropping: Growing 4 crops a year in sequence.
  - Ratoon cropping: The cultivation of crop regrowth after the first harvest, although not necessarily for grain.

- **Intercropping:** Growing two or more crops simultaneously on the same field. Crop intensification is in both time and space dimensions. There is intercrop competition during all or part of crop growth. Farmers manage more than one crop at a time in the same field.
  - Mixed intercropping: Growing 2 or more crops simultaneously with no distinct row arrangement.
  - Row intercropping: Growing 2 or more crops simultaneously where 1 or more crops are planted in rows.
  - Strip intercropping: Growing 2 or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact agronomically.
  - Relay intercropping: Growing 2 or more crops simultaneously during part of the life cycle of each. A second crop is planted after the first crop has reached its reproductive stage of growth but before it is ready for harvest.

Multiple cropping systems use land more intensively than continuous cropping or crop rotation systems and, except in arid areas, two or more crops are produced from the same land per year. This system allows land and water resources to be used more effectively throughout the period that is favourable to growing crops. The benefit to the farmers using this system are increased production, and hence increased food supply or income, the production of a large variety of crops and foods, and a lowering of the risk of total crop failure in one year. The disadvantages of the system include increased expenditure per year in implementing the system, increased labour requirements, a higher demand on the timeliness and sometimes the complexity of tillage and cultivation operations, and a higher demand on the management ability of the farmer. As multiple cropping systems generally rotate the crops following each other in a sequence, the main attributes of crop rotations described in the previous section also
apply to multiple cropping systems.

The limitations to the use of multiple cropping systems are primarily climatic and secondarily dependent on the resources of the farmer. In warm, humid regions, year-round production is possible provided that adequate water is available. In temperate regions, low temperature, low solar radiation and short day lengths may limit the length of the growing season in the winter months. Several examples of multiple cropping systems adapted to these limitations are given by Unger (1984).

When either water or temperature limits the growing season, a rapid change from one crop to the next is usually desirable so that each crop has adequate time to reach its potential yield under the prevailing conditions. Strategies for intensifying sequential cropping include using short-maturity cultivars, growing ratoon crops, harvesting crops in the immature state, transplanting slow growing crops, and using reduced or zero-tillage systems. The latter are particularly useful because of the more timely planting of the second crop, the time saved in establishing it, and the water conserved by not disturbing the soil.

Whereas sequential cropping can be used with all cultivation systems ranging from the manual to the modern high technology systems, intercropping is more adaptable to the labour intensive and animal and small tractor cultivation systems. This is because the proximity of the different crops to each other makes the use of large equipment impractical and the use of herbicides difficult, because of the difference in susceptibility of the two or more crops to a particular herbicide required for the control of a particular weed.

The use of multiple cropping systems can also be very effective in the control of soil erosion, particularly in regions where crops can be grown all year. In these regions row or strip intercropping is particularly effective as then part of the soil can be provided with vegetative cover all year, provided that the one crop is not harvested until the next is established. Furthermore, even though the whole ground surface is not covered all the time part of the surface is covered and the stems of the growing crop provide resistance to any runoff and so reduce erosion losses. In these instances grasses and other close-growing crops are especially effective at minimising soil erosion. Where crop production is limited to various seasons because of water, temperature, or other limitations, multiple cropping may enhance erosion control during the growing period, but may have no particular value for other seasons unless the use of the multiple cropping system results in more residues being produced which is then managed for erosion control. When intercropping is combined with crop residue cultivation systems then soil and nutrient losses due to erosion can be reduced to very low levels. This was demonstrated by some comparisons of soil loss for plots with multiple cropping systems and continuous cropping systems given in Section 2.2.1.3.

Unger (1984) lists several research papers, including Constantinesco (1976), Litsinger and Moody (1976) and Ofori (1974), which demonstrate that weed, pest and disease problems are generally lower in multiple cropping systems than in continuous cropping systems. The reason for lower weed problems is primarily because the various crop and weed species have different growth habits, light requirements and abilities to compete for space, water and nutrients. As each crop is planted, cultivated and harvested at times optimum to its own requirements these operations suppress weeds with different requirements. With continuous cropping systems those weed species that have the same requirements as the crop gradually become dominant amongst the weed species and lead to weed infestation, unless higher levels of weed control are used. In addition the closer management required in multiple cropping systems results in weeds being controlled on a more timely basis than in continuous cropping systems, thus reducing the overall weed problem.

For reasons similar to the above, pest and disease problems are lower in multiple cropping systems than in continuous cropping systems. The factors responsible for this include the following; use of shorter maturing varieties; greater crop diversity, including plant types,
heights, leaf density, cover, etc.; use of resistant cultivars; growing of crops at a time out of phase with the time of greatest potential for the pest species; greater diversity of habitat for predators and parasites of pest species and therefore higher predator and parasite populations; use of certain crops which exude chemicals that suppress pest populations; the greater distances between cultivars susceptible to certain pests which slows down the spread of the pests through the crop.

Although weed problems tend to be of less severity in multiple than in continuous cropping systems, the control of weeds may be more difficult, particularly in intercropping systems. This is firstly, because the use of animal and tractor drawn tillage operations are more restricted because of the proximity of the different crops to each other. Secondly, the uses of herbicides are severely limited because most herbicides cannot be used without harming some crop in the system. This latter aspect applies particularly to intercropping but also applies to sequential cropping because of the residual effects of some herbicides.
4. MECHANICAL CONSERVATION PRACTICES

The importance of soil and water conservation in sustainable and profitable crop production systems, particularly in arid and semi-arid regions, has been emphasised throughout the previous sections. The main soil and water conservation practices described in detail previously have been limited to specific tillage, cultivation and management practices. A range of additional erosion control and water conservation practices are used to complement these, and most of these can be categorised as mechanical conservation practices. These practices include the following: land smoothing and levelling; storm drains, contour ridges and waterways; terraces; gully control; and water harvesting and associated practices. A detailed description of these practices is beyond the scope of this publication. Unger (1984) gives a general introduction to these practices with numerous references.

The tillage, cultivation and management practices used to promote soil and water conservation primarily achieve these by contributing to one or more of the following:
- Protecting the soil surface from raindrop impact.
- Promoting soil aggregation.
- Reducing runoff by increasing the infiltration of water into the soil.
- Holding the water on the soil surface where it falls and reducing the speed of water running over the soil surface.

The various operations and systems used to achieve the above, and the control of soil erosion in general, were discussed in detail in Section 2.2.1.3. These included the following: the use of crop cultivation and management systems to increase crop cover and increase the soil organic matter content to increase aggregation, including the use of cover crops and catch crops; mulch farming using crop residues, although other substances such as stones, gravel, plastic films, paper, crude oil, bitumen, coal, etc. may be used for high value crops; tillage operations which increased porosity and leave a rough surface, with some modifications to reduce evaporation losses; contour tillage, graded furrows or ridges, tied-ridging, pot-holing, etc.

Mechanical soil conservation practices reduce soil erosion primarily by reducing the quantity and/or speed of water running onto or off the cultivated field and over the soil surface. The ways in which they do this vary between the different types and this will be described in the following sections.

4.1. LAND SMOOTHING AND LEVELLING

Land smoothing involves moving soil from local high points to low points in a field. From the point of view of soil erosion, this reduces the potential for water to flow to the lowest point where, depending on the general topography of the field, its concentration may lead to gully erosion. From the point of view of water conservation, land smoothing results in a more even distribution of the water stored in the field and this also increases the total amount of water that can be stored. Land smoothing is important in producing more even gradients in fields in which flood irrigation systems are to be installed. Land smoothing also aids mechanised farming in terms of the speed of operation, precision planting, weed control, fertilizing and harvesting. Although the objectives of land smoothing do not usually include reducing surface roughness, this is generally a side effect of the operation. As a rough surface is important for the control of wind and water erosion, it may therefore be necessary to carry out subsequent operations to increase surface roughness. Details of the implementation of land smoothing, and some of its side effects, are given in Section 5.3.2.6. It should be noted that many authorities use the terms land smoothing and land levelling interchangeably.

Land smoothing is generally conducted on a fairly small scale and does not generally change the average slope of the field. In contrast, land levelling includes the objectives of land smoothing but an important additional objective may be to reduce the slope of the field so as to
reduce the speed of runoff, and also to increase the length of time that the water remains on the surface so as to increase total infiltration. Land levelling is particularly important with regard to flood irrigation systems. Land levelling will be discussed further in the section on terracing.

When the depth of topsoil is shallow and the land is uneven then care needs to be taken that the topsoil left on high points is not too shallow for later cultivation. If it is not practical to bring in topsoil from outside of the field then the topsoil from the high and low points should be scooped off and left to one side. The subsoil is then transported from the high points to the low points to smooth the field surface. Once this has been completed the exposed subsoil is covered with the topsoil.

Animal or tractor drawn damscoops are used to move the soil when there are distinct low and high points in the field. Following this operation, or as a first operation on less uneven fields, landplanes are used. These are usually tractor drawn, but simple animal drawn equivalents made of wooden poles or boards can also be used. Further details of the equipment used and the implementation of these operations are given in Section 5.3.3.

4.2. STORM DRAINS, CONTOUR RIDGES AND WATERWAYS

As the slope of a field increases the potential for runoff and erosion normally increases. Storm drains, contour ridges and waterways are very important components of any comprehensive soil erosion control system on lands subject to potential erosion due to their slope and the possibility of intensive rainstorms.

Storm drains are channels and ridges constructed above the field to divert water from flowing onto the field from areas above the field. Contour ridges, also known as diversion terraces, are channels and ridges constructed within the field and across the slope to divide the field into shorter downslope lengths, and to convey the excess water off the field at non-erosive speeds. The amount of runoff flowing over a particular point is the accumulated total of all the runoff upslope of that point, unless it is diverted away. The greater the quantity and the faster the flow the higher the erosive power of the flowing water. By dividing the field into shorter downslope lengths, by the use of contour ridges, the mean amount of the water flowing down the slope over the whole field is reduced by a factor roughly equal to the number of contour ridges. Waterways are required to collect the water from the exits of the storm drains and the contour ridges and to convey it non-erosively from the field to either streams or wide, reasonably level areas where the energy of the water can be dissipated without resulting in erosion.

Generally, for fields with slopes steeper than 1% to 2% it is desirable to use storm drains, contour ridges and waterways to control erosion. On some highly erodible soils in regions subject to high intensity rainstorms these measures may be required on lesser slopes. Storm drains and waterways are also required for more level fields where runoff from areas above the field or from roads, etc., may occur.

The design of mechanical conservation layouts is complex and beyond the scope of this publication and are described in detail in Elwell (1980) and Wischmeier and Smith (1978). A number of factors need to be considered in the design including the following: general topography of the field and neighbouring areas; slope of the field; the soil's texture, infiltration rate, erodibility and depth; estimated maximum rainfall intensity and duration and hence maximum runoff; "acceptable" erosion limits; means of construction of the conservation works; etc.

The main design variables for contour ridges are their spacing, length, width, height, gradient and position with respect to the contour of the land. The spacing of contours is closer as the following factors increase: slope, maximum anticipated runoff and soil erodibility. As the
length of a contour increases the volume of water that the downstream end carries increases for a given runoff, and this limits the length of a contour for a given height. Furthermore, on unprotected channels the soil erodibility also controls length as the erosive power of the water increases with the volume of flow.

On fields with gentle slopes and deep topsoil the broad-base channel and ridge are commonly used. With this type, the channel and ridge are cropped, usually the same as for the area between the ridges. This system minimises the field area lost to conservation works, and also minimises interference with mechanised operations. On fields with steeper slopes the narrow-base channel and ridge, with steep backslope ridge, are commonly used. However, this type is also used on gentle slopes to minimise the amount of soil movement required for their construction. This type is usually grassed, both to eliminate any possible erosion losses in the channel and to stabilise the ridge. The selection of appropriate locally-adapted grass species which will both prevent erosion, stabilise the channel and ridge but minimise invasion into the field, and so create weed problems, is very important. In some regions the conservation ridges are used to grow grass species that both meet the above requirements and are also suitable for use as fodder.

The gradient of the contour channel should be such that the water flows at a non-erosive speed for a given soil. A commonly used gradient is 1 in 250, i.e. a 0.4% gradient. On uneven slopes steeper gradients can be used to ensure that overtopping of the ridge does not occur during heavy rainstorms. Gradients can also be varied along a contour ridge to improve the alignment of the contour ridges with each other to facilitate mechanised operations. This is very important as if the layout impedes mechanised operations then the costs of the implementation of the cultivation operations will increase. In addition to this the farmer or equipment operators may be tempted to ignore the conservation ridges in an awkward layout, and for example plough over them, which will rapidly destroy the conservation works.

Waterways may be natural, running down low points on the land, or may be specially constructed. Waterways are usually broad and shallow and constructed up and down the slope as the contour channels are designed to empty into them. Their slope is therefore generally determined by the slope of the field and they have to be grassed to prevent soil erosion occurring within them. Again it is important that appropriate grass species are selected as described above. Appropriate grass cover will generally protect broad and shallow waterways up to a slope of about 15%. On steeper slopes drop structures of stone or other materials are required at intervals along the grassed waterways. On very steep slopes the waterways may need to be paved with stone. Although costly, this method has the advantage that the waterway can then be used as a path to the field. Unpaved waterways should not be used for traffic as the tracks of the vehicles or animals leads to erosion in the waterway.

Storm drains, contour channels and ridges and waterways can be constructed manually or by using ploughs, damscoops or graders. For a comprehensive scheme the amount of soil that has to be moved is high and hence the energy expenditure is high. Although conservation works can be constructed manually the amount of work involved frequently limits the implementation of schemes when this is the only means of construction. The use of animal draught power substantially reduces the amount of time and labour involved when compared to manual construction. The use of animal drawn damscoops is a very effective way of constructing conservation works and the methodology involved is described in detail in AGRITEX (1986-1991). When tractor draught power is available, then ploughs and graders are the most commonly used implements for the construction of conservation works. Damscoops are further described in Section 5.3.3.1.

Although storm drains, contour ridges and waterways are very important components in any comprehensive system to control erosion on a farm, there are several important factors that limit their implementation. Firstly, as the contour channels and ridges are often not cropped and as waterways are never cropped, conservation works reduce the amount of area
available for cropping in a particular field. This is a particularly important restraint on small farms. Secondly, to be most effective conservation works should cover a major portion of the watershed. Where farms are small this requires that several farms be covered in one system. This usually results in one farm being more adversely affected than another in terms of reduced cropping area, which may lead some farmers to be reluctant to participate in the programme. Thirdly, the cost of implementing and maintaining the conservation layouts is high. Fourthly, large and efficient extension agencies are required to promote and design the conservation layouts.

In addition to the above points some caution is required in the use of conservation works. Firstly, there is a tendency to think that because they are being used that further in-field protection of the soil is not required. This is not the case, as soil lost from the cropped areas to the contour channel and waterway is very seldom collected and returned by the farmer. Secondly, if soil and water conservation practices are not adopted within the field, then the amount of runoff can be great. The water runoff is then concentrated into the waterways and can then pose the danger of gulley erosion further down the slope, unless comprehensive systems covering the whole watershed are implemented and maintained.

For the successful adoption and use of conservation works the following points need to be emphasised:

- Farmers must be aware of the need for conservation works in terms of their own future and economic benefit.
- Conservation works should be part of a comprehensive plan to conserve soil and water on the farm as discussed in Section 2.2.1.3.
- The design of the conservation layout must satisfy the requirements of soil conservation, as well as balance the following:
  - Minimise cost of implementation of the system.
  - Minimise future maintenance requirements.
  - Minimise the area of the field that cannot be cropped due to the conservation works.
  - Minimise interference with future efficient mechanised operations so as to minimise the cost of crop production.
- Efficient extension agencies need to be in operation to plan and mark out the layouts.
- Assistance or incentives may need to be made available to farmers to promote the implementation of the systems, e.g. food for work schemes, access to credit, mechanised implementation agencies, etc., however, the drawbacks of these schemes also need to be considered.
- Government departments must be aware of the above requirements and be orientated to achieving them. They should be included in government policies and ideally a comprehensive conservation strategy should be developed and implemented as discussed in Section 2.2.3.

4.3. **TERRACES**

Whereas contour ridges are used to reduce the downslope length of a field, terraces are used to both reduce the slope of the field as well as the downslope length of the field. It should be noted that some authorities use the term terracing to include contour ridges, and that they refer to the terraces described here as bench terraces.

Terracing is the levelling of strips of land down a slope in the form of a series of steps. The cropped levelled strips are shaped to have a lower gradient than the original slope but are not usually completely level. By reducing the gradient the speed of any runoff is reduced. The length of the downslope levelled strip is designed on the same basis as the distance between contour ridges, to limit the amount of runoff flowing over the cropped areas. Runoff is diverted from the field at the beginning or end of each terrace in a manner similar to that used for
contour channels and ridges. These two complementary factors substantially reduce erosion losses. The land levelling process also involves land smoothing and, as discussed earlier, this evens the distribution of the water over the field and increases the total amount of water that can be stored in the field.

Where the slopes of the stepped ends of the terraces are very steep, they are usually supported with stone, brick or wood. On very stable soils, or for terraces with more gently sloping steps the ends can be supported by vegetation. A detailed coverage of terraces is given by Hudson (1981), Gil (1979) and Barber et al. (1980).

The slope of the terrace may be horizontal, or slope outwards or inwards. Each is usually adaptable to a particular type of crop or condition. On steep lands the use of terraces may be the only way in which the land can be used for crop production on a sustainable basis. However, because of the large amount of work involved in constructing terraces on steep lands they are seldom part of modern development programmes, and these lands are usually used for alternative production purposes. In certain countries some remain from another era and are highly important for crop production.

Terraces are only used on land where the use of contour ridges and conservation tillage practices do not reduce the potential erosion down to acceptable limits, and where their cost of construction does not exclude their economic viability. Unger (1984), reports on a method advocated by Barber et al. (1980) and Jacobsen (1966, 1968), which minimises the labour and cost requirements for constructing terraces. This involved constructing contour ridges but placing the soil uphill of the channel rather than the usual downhill placement, and then stabilising the ridge with grass, or stone, etc. The natural process of erosion and tillage then leads to deposition of soil behind the ridge, which gradually reduces the slope thus forming a terrace. To accommodate this deposition the ridge or wall has to be periodically raised.

The width of the terrace is determined primarily by the steepness of the land, the acceptable height of the terrace step, and the depth of the soil. Although a level terrace results in least erosion the cost of construction and the use of machinery may determine that an acceptable gradient is more desirable. Generally, the greater the gradient the lower the cost and the wider the terrace. The wider the terrace the more suitable it is for mechanised agriculture. To accommodate larger equipment terraces should be positioned parallel to each other and at intervals compatible with equipment widths or multiples thereof. A range of methods can be used to achieve good terrace alignment, including land forming, extra cut or fill along the terrace, multiple outlets, variation in grade, channel blocks, etc., and these are described in the Soil Conservation Service (1977). It is important that terraces are properly designed and compatible with farmers’ equipment, as they are then more likely to be adopted and maintained for soil and water conservation.

4.4. WATER HARVESTING AND ASSOCIATED PRACTICES

Water harvesting, runoff farming and water spreading, involve collecting water runoff from areas which are not cropped and concentrating the water into areas which are cropped to increase crop yields. This is done both on a macro-scale and a micro-scale depending on the practice. Unger (1984) reviews several methods and lists relevant references. Some of the methods are summarised below:

- Runoff collected from natural watersheds, e.g. hills or steep sloping fields, and spread onto a cropped field. Storage of water is normally limited to that stored in the soil but the flexibility of the system can be expanded if the water can be stored in small dams.
- Runoff collected from areas upslope of the field treated with asphalt emulsions, water repellents, etc., to enhance runoff.
- Conservation bench terraces are a variation of the above where the upslope area is
smoothed to provide runoff and the downslope area levelled so as to retain the runoff water for cropping.

- Micro-catchment water harvesting is basically a broad based ridge and furrow system, with the ridge providing the runoff and the crop grown in the furrow. Ridge spacing is usually 1 to 1.5 m and the furrows can be dammed. For high value crops it may sometimes be economically viable to cover the ridges with plastic film to enhance runoff and reduce weed growth.

- Micro-watersheds and vertical mulches are sometimes combined in a system in which water runoff from part of a field, e.g. a strip in between widely spaced crop rows, is concentrated into an open residue-filled slot, adjacent to the next crop row.

4.5. IRRIGATION AND DRAINAGE

The use of irrigation for crop production is extremely important in many regions of the world. Drainage is also very important in regions subject to periods of high rainfall and it is also an intrinsic component of any well designed irrigation scheme. Both of these are major subjects in their own right and are thoroughly covered in numerous publications. They will therefore only be treated briefly in this report, with the emphasis placed on tillage and soil and water conservation.

4.5.1. Irrigation

Irrigation is the prime means of increasing crop production in regions where the main factor that limits growth is a shortage of water, and where this limitation cannot be overcome by using rain-fed conservation tillage or water harvesting systems. Supplies of suitable water for irrigation need to be available and to be capable of being supplied to the field, and applied within the field, at acceptable overall costs. The installation of irrigation systems involves a high capital investment that can only be recouped by higher yields. Although the supplementary supply of water is the main factor involved in the yield increase, tillage plays an important role in the overall irrigation layout and in the even distribution of water over the field, in maximising the yield, and most importantly as one of the important components in the management system used to prevent the degradation of the soil through salt deposition. There are numerous publications in this field with FAO (2002) covering the design, implementation and management of irrigation systems for field assistants in detail.

There are three main types of irrigation system, which can be distinguished by the means in which water is conveyed to the field and the way it is distributed within the field:

- **Surface Irrigation.**
  Water is transported to the field by open canal, or occasionally by pipes, and usually under gravity. The water is applied to the field by an open furrow system of flooding into furrows, basins or flooding of the whole field.

- **Sprinkler Irrigation.**
  Water is pumped to the field in a pressurised pipe system. Water is applied to the field by aerial spraying through sprinklers. A large range of systems are used including the pipe and standing sprinkler, semi-automatic mobile systems such as the centre pivot, water cannons, and micro-sprinkler systems, etc.

- **Trickle or Drip Irrigation.**
  Water is pumped to the field in a pressurised pipe system. Water is generally applied to the field through a semi-permanent system of pipes and tubes, which feed water very slowly to a large series of discrete points and usually to the base of individual points.

The type of irrigation system used determines the amount of land preparation required for the installation of the irrigation system, and it may also determine the tillage system to be used. Poor land preparation may cause substantial losses of irrigation water, or at least their
In surface irrigation systems, where water flows across the field surface, the field should be level or have a uniform gradient to enable all areas to receive the same application of water. In these systems land smoothing or levelling is usually required for the uniform distribution of water. In surface irrigation systems the soil surface forms the water distribution system within the plot and hence the final tillage operations required are largely determined by the distribution system chosen, i.e. ridges and furrows for furrow irrigation, broad flat basins with ridges for basin irrigation, and a completely flat surface for flood irrigation. The equipment to implement these systems, viz. ridgers, bed shapers, levellers, landplanes and damscoops, are described in Section 5.3.

In sprinkler systems land preparation is less critical than for surface irrigation, but significant irregularities in the land surface can result in an uneven collection and storage of water. Providing the land surface is not too uneven this can be overcome by the use of tillage operations such as tied-ridging, where the water is held where it falls. The retention of crop residues on the soil surface, as opposed to clean tillage systems, can also result in a more even distribution of water on uneven land although this is not as effective as tied-ridging. Generally, little land preparation over that required for rainfed cropping is needed for trickle irrigation systems, due to their steady low rate application characteristics. However, as land smoothing assists mechanisation operations and as trickle irrigation systems are generally not mobile, land smoothing may be desirable before they are installed.

A further important characteristic of irrigation, which determines the system layout and the tillage system chosen, is that irrigation water usually contains salts in solution that remain in the soil after the water has evaporated. The poor design and management of many irrigated lands throughout the world has resulted in these lands having to be abandoned due to this problem, despite the large amount of capital invested in them. To deal with this problem it is essential that the drainage system is treated as an intrinsic component of the irrigation system. Furthermore, the minimum amount of water should be applied to obtain the desired yields. This procedure also minimises the water cost. Periodically excess water is used to leach accumulated salts into the subsoil. If water is regularly applied at a rate in excess of requirements, but less than that required to leach the salts into the subsoil layers, then the wet soil surface will have a high evaporation rate which will lead to excessive amounts of salts accumulating in the topsoil.

To meet the above requirements it is important that the tillage operations selected produce a soil with the following characteristics:

- A high infiltration capacity and good internal drainage. This minimises the amount of time that the soil surface remains saturated and is thus subject to the maximum evaporation rate. This also allows the very important management system of leaching accumulated salts into the subsoil.
- A good water holding capacity down to an adequate depth. This maximises the length of time in between irrigation episodes and so minimises the time that the soil surface is saturated and prone to maximum evaporation.
- Evaporation should be minimised where possible through the use of a mulch. This is generally only feasible on sprinkler and trickle irrigation systems.

The first two characteristics can be achieved by using tillage operations and systems that increase and maintain a high level of soil aggregation and especially a high proportion of water stable aggregates. In addition to this it is important that hard impermeable layers in the soil are broken up to improve drainage and increase water-holding capacity. It is also important that steps are taken to minimise the reoccurrence of compaction problems.

Under irrigation dense impermeable layers are sometimes formed deliberately, as in puddling for paddy rice production, and the soil can be made homogeneous again through inverted ploughing operations. Crusting can also result from the application of water, especially
under sprinkler irrigation systems, and deeper compaction can result from the repeated wetting and drying cycles. Compaction also results from the formation of plough pans or wheeled traffic operating in the field when the soil is excessively moist, as discussed in Section 2.1.2.7.

In hot climates tillage, and especially deep tillage, should be carried out shortly before the growing season, in order to minimise the loss of soil organic matter through aeration. Tillage operations aerate the soil which speeds up the decomposition of soil organic matter, i.e. the mineralisation and nitrification of the soil organic matter is speeded up. The nitrogen is then more likely to be leached away by the irrigation water and the loss of soil organic matter will lead to poorer soil aggregation. These aspects were discussed in Sections 2.1.3. and 2.3.2.2. In irrigation systems good water management systems are designed to minimise the loss of nutrients through leaching. However, as water management is also used to deliberately leach accumulated salts into the subsoil it is important that fertilizer applications are split and timed to minimise leaching.

An important benefit of irrigation is that soil can be brought up to the optimum moisture contents for specific tillage operations. This assists in achieving the optimum results from the tillage operation as well as in savings in energy and time. The timing of water application also needs to take into account that the soil is impassable for tillage operations for some time after the application of water.

The efficient use of irrigation water is very important in order to maximise yield, minimise costs, and to minimise damage to the soil both through the accumulation of salts and through erosion. A well designed irrigation system is based, among other factors, on soil water infiltration rates, soil water holding capacity and water availability. Regardless of the irrigation system used, water is mainly lost through deep percolation or runoff, or both. Assuming an adequate design of the irrigation system, Unger (1984) lists application techniques that result in low efficiencies and water losses, and the possible consequences, and these are listed below:

- **Time of application too long:**
  - Excessive deep percolation.
  - High amount of runoff.

- **Time of application too short:**
  - Poor water distribution.
  - Low amount of water storage in soil.

- **Rate of application too high:**
  - High amount of runoff.
  - Low amount of water storage in soil.

- **Rate of application too low:**
  - Poor water distribution.
  - Excessive deep percolation at input site.
  - Low amount of water storage at other sites.

- **Water applied too frequently:**
  - Excessive deep percolation.
  - High amount of runoff.

- **Water applied too infrequently:**
  - Excessive infiltration.
  - Poor water distribution.

Aside from considerations of efficiency, potential erosion also needs to be considered. This is discussed in Section 2.2.1. and the same factors apply in irrigation schemes. However, two additional points do need to be made. One aspect of irrigation systems that reduces the potential for erosion is that they are usually laid out on fairly level ground, thus reducing the speed of any runoff, and should have well designed water control and drainage systems. One aspect that increases the potential for erosion is that infiltration in wet soil is much lower than in dry soil and so if a rainstorm occurs when the soil is saturated shortly after being irrigated then runoff will be high. The design of gradients and the application of irrigation water should be
such that erosion due to the application of water in well-designed and managed systems is minimal. Because of the ability to manage water supply in irrigations systems the cropping system can be designed to provide increased crop cover during periods when there is a high erosion potential due to water or wind erosion. As moist soil is less erodible by wind than dry soil irrigation can also be used to moisten the soil prior to periods of high wind erosion potential.

4.5.2. **Drainage**

Long periods of excessive soil water levels, or waterlogging, can be as detrimental to crop production as too little water. Problems of excess water and poor drainage are usually most severe in high rainfall areas, but can also occur in drier areas. Furthermore, as outlined in the previous section drainage, is a very important component of any well-designed irrigation system. Drainage is covered in detail in numerous publications, including Luthin (1957) and Schilfgaarde (1974).

Waterlogging interferes with the growth of most dryland crops primarily because their roots need to have a good supply of oxygen for them to efficiently absorb nutrients from the soil. Avoidance of waterlogged conditions is particularly important during germination and emergence.

Where excess water and poor drainage are problems, water must be conveyed from the land at non-erosive speeds to protect the soil. Surface water is normally removed from the land by contour ridges and channels, waterways and canals, etc. Whereas the water is usually removed under gravity flow, in some low lying areas the water has to be pumped across dykes for final discharge from the area. Tillage operations can be used to promote internal drainage by increasing soil porosity by increasing soil aggregation and especially the proportion of water stable aggregates; by increasing fracturing and breaking up impervious layers in the soil, and so improving drainage into the subsoil. Subsoil drainage can be promoted by the use of mole drains or the more permanent laying of lined drains into the subsoil, which discharge into low lying areas or canals, etc.

Major drainage systems often involve large farms or numerous small farms operating on a cooperative basis. Drainage on a small-scale is also commonly used by individual farmers. The systems used include the above tillage and subsoil drainage operations as well as the use of ridges and beds. On lands with slight gradients prone to waterlogging, ridges are frequently constructed down the maximum slope, but these should always be set at gradients that convey runoff at non-erosive speeds. The crops are planted on the top of the ridges and even on level land under waterlogged conditions the top of the ridges drain into the furrows. Beds can also be used with the water from the beds draining into the furrows.
5. **POWER SOURCES AND TILLAGE, PLANTING AND FERTILIZING OPERATIONS AND IMPLEMENTS**

The previous sections have dealt with the properties of soils, the various factors to be considered when selecting a tillage system appropriate to a particular situation, and the main factors to be considered when analysing problems relating to tillage. Tillage systems and the ways in which the different cultivation and management systems can be used to complement the main attributes, or compensate for the main deficiencies, of the tillage system being used have also been discussed. The importance of soil and water conservation in sustainable and profitable crop production systems, particularly in arid and semi-arid regions, has been emphasised throughout the previous sections. The last section covered the mechanical conservation practices used to complement the soil and water conservation aspects of some tillage, cultivation and management practices.

This section will cover the means of implementing the various tillage operations. It will include the power sources used, the detailed objectives and effects of tillage, planting and fertilizing operations, the implements used and some basic information on their adjustment, and the means of implementing operations in the field. Later sections will cover some basic principles of the maintenance of the equipment and their costs. Prior to proceeding it is considered important to place the selection of power sources and tillage operations within the broad context of agricultural mechanisation.

### 5.1. **AGRICULTURAL MECHANISATION**

Agricultural mechanisation is the process of improving and increasing the use of agricultural implements and machinery in agricultural production operations, so as to maximise the effectiveness and efficiency of the implementation of these operations. Agricultural mechanisation is discussed in detail by Crossley and Kilgour (1983), and a summary of the main objectives of mechanisation is given below:

- **To increase crop production by:**
  - Increasing the yield per hectare by:
    - Improving the timeliness of operations.
    - Improving the quality of operation.
    - Enabling the application of yield increasing inputs, e.g. pesticides, irrigation water, etc.
  - Increasing the area under cultivation by increasing the amount of work that can be done in the time available.
- **To enable crop or livestock production, which was previously impractical due to the lack of mechanisation, e.g. provision of refrigerated milk collection point for smallholder milk projects.**
- **To release labour for other requirements, e.g. the mechanisation of operations on low value staple crops could release workers for production of more labour intensive high value crops.**
- **To generate off farm employment opportunities in the manufacture, supply and servicing of the machines.**
- **To improve the quality of life of farmers by reducing the drudgery involved in farming operations.**

A qualification of the first objective listed above does need to be made, and that is that under most farming conditions the main farming objective is to increase output per unit input of labour or finance, rather than solely to increase output. The cost and benefit of each operation needs to be taken into account and this applies equally to subsistence farmers as to commercial farmers. It is only the criteria by which the costs and benefits will be measured which differ between the two groups.
Agricultural mechanisation will not be discussed in detail here. However, the above objectives need to be borne in mind, together with the objectives of the tillage operations, when the means of implementing the tillage operations are being considered.

5.2. **POWER SOURCES**

The mechanisation options open to the farmer largely determine the possible range and quality of work that can be undertaken and these in turn will determine the range of possible crop production systems. The mechanisation options are primarily determined by the available power sources. There are three main categories, or levels, of power sources used for implementing tillage operations, namely, manual labour, animal draught power and engine power, i.e. tractor draught power. All three are in common use in the world. Furthermore, many farms use a combination of two or three of these power sources. On most farms where animal draught power (ADP) is used manual labour is still very important for the implementation of some operations, e.g. weeding and planting. There are also many farms that have access to tractor power in the form of contractual ploughing, which also use ADP and manual labour for other operations.

The choice of which power system to use depends on a number of interacting factors including the resource base of the farmer, farm size and terrain, climate, the crop production system, the power and draught force requirements of specific tillage operations, available infrastructural support, etc. Generally, higher power sources enable higher draught forces to be exerted, higher work rates, improved timeliness and a higher quality of operation to be achieved, as compared to lower power sources. However, their cost in terms of capital costs and financial risks are also higher. It is very important that higher levels of power sources are not automatically seen as more desirable than lower levels. Most tillage operations that can be carried out using tractor draught power can also be carried out by either ADP or by manual labour. The main exceptions to this are subsoiling operations, deep ploughing and powered rotary tilling. It is therefore important that the power source, or combination of power sources, appropriate to the farmer's resource base, and farming environment is chosen.

A comparison of some of the main characteristics of manual, animal and engine power is given in Table ___(@ Elliot 1989, p 7, Table 2), and these aspects are more fully discussed by Crossley and Kilgour (1983). Table ___(@ Elliot 1989, p 5, Table 1) gives a comparison of the work rates characteristic of the main power sources. These should be viewed in relation to the farm size and the labour availability, and hence whether the various operations can be completed in a timely manner. If for a given situation the operations can be completed in a timely manner with the available power sources, then moving up to a higher power source level is unlikely to significantly increase output but will substantially increase costs.

In terms of higher work rates, or power, the step between manual labour and ADP is generally much larger than that between ADP and tractor power. In terms of higher capital cost and financial risk the step between ADP and tractor power is generally much higher than that between manual labour and ADP. However, if looked at in terms of overall costs per hectare then tractor power is frequently the most cost effective power source available. The financial aspects will be discussed further in Section 6.

Only a brief overview of the main characteristics of each of the main power sources will be given here. The efficient use of power sources and the matching of implements appropriate to the power capabilities of the individual power source is fundamental to the efficient implementation of tillage operations. A lot of information is available on these subjects and it is beyond the scope of this publication to cover this field in depth.

A summary of the units and main formulae for force, work and power is given below:

- **Force** = mass x acceleration

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A summary of the units and main formulae for force, work and power is given below:

- **Force** = mass x acceleration
Units: N - Newtons, where 1 N = 1 kg m/s power 2
(Note: Weight = mass x acceleration due to gravity (g), where g = 9.81 m/s²).

- Energy = work = force x distance
  = power x time
Units: J - Joules, where 1 kJ = 10³ Nm
- Power = work per unit time
  = force x speed
Units: W - Watts, where 1 kW = 1kJ/s

5.2.1. Manual Labour

A healthy and well fed human adult has a sustainable power capability of about 0.07 to 0.1 kW and can exert a pull of around 0.1 kN (Crossley and Kilgour, 1983). A common use of manual labour on the farm involves the use of the hand hoe or the operations of machines, e.g. threshing, milling, etc. Although the unaided force exerted by a human is relatively low, the forces applied can be very high, e.g. through the use of momentum, as in the pick, or through the use of a leverage system, as in the oil expeller.

Due to their low power capability the work rate of humans is very low compared with the other main power sources. However, the common work rates can frequently be increased several fold by improving the design of implements and by increasing the efficiency of the operation by means of time and motion study, etc. For example, the heavy, short handled hoe often used for primary cultivation is also used for weeding in many regions, whereas for weeding, a light, long handled swan neck hoe allows a more upright working position, is lighter to use and more manoeuvrable, and its use can result in a significantly higher work rate. Another example is of a simple hand pushed wheeled weeder which can control small weeds at a rate several times faster than a long handled hoe.

Unfortunately, manual labour is too often seen as intrinsically slow with little thought given to ways in which the work rate can be speeded up without demanding a higher work output from the workers. It is very important that the design of improved implements should also aim to reduce any operating strain to the workers, as this both improves the health and safety aspect for the worker as well as increases the amount of work which can be carried out. Numerous publications cover this field and give illustrations of the equipment available.

5.2.2. Animal Draught Power

The main draught animals used are cattle, water buffaloes, donkeys, horses and camels. The sustainable draught force capable of being exerted by healthy, well fed and correctly harnessed animals is generally taken as being between 10% to 14% of their body weight. This varies slightly between species but can be used as a rough guide for all. It should be noted that variations of weight within species is high and this particularly applies to cattle. For example, the weight of cattle used for draught purposes commonly varies between roughly 200 kg and 600 kg, depending on breed. On this basis the sustainable pull of a team of oxen with a combined weight of 1200 kg would be between roughly 1.2 kN and 1.7 kN.

Draught animals can exert much larger forces, of around 5 times or more of their sustainable pull, for short periods if compensated with adequate rest periods. Furthermore, under shock loads, e.g. pulling a tine against an underground obstacle, animals can exert an instantaneous force equal to their own bodyweight. Animal drawn equipment therefore needs to be designed with a factor of safety of around 5 to 10 times the continuous draught force in order to minimise breakages and delays in the field.

The operating speeds of draught animals varies roughly from 0.5 m/s (1.8 km/h) to 0.9 m/s (3.2 km/h), with cattle being at the slower end and horses at the faster end. As power is
equal to force times speed, a team of oxen exerting a draught force of 1.2 kN at a speed of 0.7 m/s would be producing a power of 0.84 kW.

The length of time that animals can work per day varies from roughly 4 to 6 hours depending on the species, the condition of the individual animal and the type of work. For optimum work efficiency resting periods are also required during the working day as well as brief rests in the field. For example, the brief rest that the animal has during headland turning is important and the length of the plough furrow should not be longer than 150 m in order to achieve the required frequency of rest periods.

An important factor in ensuring an efficient output of work from draught animals, particularly because of their low power capability, is the matching of the power requirements of the implement to the power capability of the draught animal team. The power requirements of well designed implements are reduced by selecting those with narrower working widths, or operating them at shallower depths. The power capabilities of the draught team are increased by increasing the numbers of animals in the team or selecting heavier animals. For very light operations single animals can be used but unfortunately this is seldom done due to the frequent lack of suitable harnesses. However, for light draught work even simple harnesses made of sacking material and ropes are suitable for a single harness. The matching of the implement to the draught team is usually based on the experience of the operator in observing whether the animals are straining or not. Remembering that power is equal to force times speed it may be expected that if a light implement is attached to a strong team that the animals will simply move faster. However, draught animals have a narrow range of working speeds and any increase in speed will only marginally compensate for any substantial excess of power capability over power requirement.

Again, because of the low power capabilities of draught animals, it is particularly important that animal drawn implements are designed to achieve their tillage objective while requiring the minimum amount of draught force to do so. This applies to the initial design of the implement as well as to the maintenance of the implement to retain any sharp edges at the correct angle. It is also very important that the role of the operator is not overlooked. For example, to plough a 1 ha plot with a mouldboard plough with a 250 mm share requires the operator to walk approximately 40 km. The stability of the plough is important to minimise the strain on the operator and the lighter the plough the easier it is to handle at the headlands.

Good nutrition, good harnessing and the training of animals and operators are all extremely important if a good work output from the animals is to be achieved. Good nutrition is fundamental as the draught power capability of a draught animal is proportional to its weight. Maintenance feeding is required to maintain the weight of animals during dry winter periods when there may be a shortage of grazing. The main weight gain periods occur when there is abundant grazing. The small size of many draught animals is frequently due to poor nutrition rather than genetic limitations. Although programmes can be instituted to increase the weight of draught animals it does need to be borne in mind that heavier animals require more feed and this is frequently the limiting factor. Supplementary feeding is desirable during heavy work periods to provide extra energy to prolong the working period.

The harnessing requirements are specific to each species and it is important that the correct form is used for each, to ensure that the optimum work output is achieved and to ensure that the animal is not injured. The yoke or harness is the medium through which the power is transmitted from the animal to the implement. The contact area between the animal and the yoke or harness should be maximised to reduce the contact pressure so as to allow the animal to exert force without hurting itself. If the contact point is painful the animal will not exert the amount of force that it is capable of, which will reduce its work output, and will also result in injuries. Yokes should be used for cattle and water buffaloes, whereas harnesses should be used for donkeys, horses and camels. The poorly designed and fitting yokes and harnesses commonly used significantly reduce the potential work output from the animals.
The extension of good ADP use practices is very important for its efficient use. The training of extension staff, should include general animal husbandry, selection and breeding of draught animals, nutrition and maintenance and supplementary feeding, training of draught animals, design of yokes and harnesses and their appropriate use, field operation of animal drawn implements, etc.?

Although for many years the use of ADP was neglected, it has become increasingly seen to be the main means by which the sustainable crop production and the profitability of most small-scale farmers in Africa can be increased. As can be seen in Table ____(@ Elliot 1989, p 7, Table 2) it has several distinct advantages for small farms. Furthermore, as shown in Table ____(@ Elliot 1989, p 5, Table 1) it enables operations on small farms to be completed in a timely manner. On these farms the use of tractor power would generally not be economically viable unless used very efficiently on a multi-farm basis.

As Starkey (1986) points out, although animal traction itself may seem an intrinsically simple technology, it should be viewed as one component of highly complex farming systems. Interactions within these systems involve the soils, crops, and animals, but also the prevailing ecological, social and economic conditions. Some aspects of these were briefly discussed in Section 2.6.2. In countries where there is a long tradition of animal traction technology then the improvement and promotion of this technology is relatively straightforward. However, even in these cases a comprehensive approach is required if meaningful results are to be achieved. The approach needs to cover all aspects of ADP mentioned above as well as those aspects concerning the supply, distribution, sale and servicing of ADP implements. In countries where there has not been a long tradition of ADP use then far more substantial intervention is required. Because of the complexity of the farming and environmental conditions, it is very important that lessons learnt from animal traction promotion programmes in one country or region are studied and incorporated into any new programmes. Various networking projects have been established to facilitate this transference of experience and this is outlined by Starkey (1986).

5.2.3. **Engine Power**

A very large range of power units and traction vehicles are used for crop production. These range from small 1.5 kW single axle tractors, controlled by the operator walking behind them, to large 4 wheel drive articulated tractors of over 250 kW in power.

The draught forces capable of being exerted by traction vehicles are dependent on the power of the engine, the gearing between the engine and the drive wheels, the weight on the driving wheels, tyre configuration, soil conditions, etc. For tractive purposes the maximum draught force can generally be taken to be 60% to 70% of the weight on the driving wheels, and the maximum draught power available to be 60% to 80% of engine power, with both depending primarily on field conditions.

The main advantage of tractor draught power over manual labour or ADP is the very much higher work rate that can be achieved. Also of importance are the higher draught forces that can be exerted which allow a wider range of operations to be carried out and usually a higher quality achieved in their implementation. As can be seen in Table ____(@ Elliot 1989, p 7, Table 2) tractor power has several distinct advantages for medium to large farms, or for use on a multi-farm basis. However, there are several major disadvantages to the use of tractor power and these are mainly due to their high cost, frequently in scarce foreign exchange, and the considerable infrastructural support required for their efficient operation. The infrastructural support required, includes; fuel and oil supply; dealership networks for the supply of spares and new tractors and implements; well equipped servicing and maintenance facilities; trained and experienced mechanics and operators; training facilities for mechanics and operators; the
required credit and financial infrastructure; and ready access to foreign exchange for those items not resourced or manufactured locally. For resource-rich farmers on medium to large-scale farms, farming in regions with the required infrastructural support, tractor draught power is usually the most efficient form of draught power in terms of profitability. However, for those farmers who do not fit into this category the use of tractor draught power can be financially disastrous. There are numerous examples of mechanisation programmes based on the use of tractor power, without the necessary preconditions for their introduction having being met, that have failed and resulted in the loss of large financial resources and the personal hardship of the farmers and their families.

Assuming the required infrastructure is in place then the selection of the size of tractors appropriate to a particular farm or situation is dependent on a number of factors, including; the size of farm; the operations required to be undertaken and their relative frequency; soil conditions and tillage systems; transportation requirements; financial resources of farmer and cost of tractors; availability of tractors and matching implements; existing tractors on the farm; whether single-farm or multi-farm use is planned, etc.

There was significant interest in the 1970's and early 1980's regarding the use of small tractors in developing countries, i.e. tractors generally below 15 kW in power. However, after many trials the main conclusion was that they were not appropriate due to the relatively high cost of small tractors in terms of their cost per kW compared to large tractors. Furthermore, the draught power capability of small tractors was generally not much higher than that of a good team of draught animals, but the cost were much higher. This matter is discussed in detail in Agricultural Engineer, volume 33.

Due to the high cost of tractors their efficient operation is of prime importance. Due to their high capital cost tractors are generally not economically viable unless their productive usage is high. This can be achieved even on small farms by their use on a multi-farm basis, either through machinery rings or on a contractual basis, and these are discussed further in Section 6. Due to their high running costs tractors should be operated as efficiently as possible. This includes both fuel costs as well as minimising repairs due to incorrect operation. To minimise fuel costs the following steps should generally be taken:

- Tractors and implements should be matched to each other and to the main operations that they are planned to carry out.
- Implements should be correctly adjusted.
- Tillage operations should be carried out when the soil conditions are appropriate to the tillage operation.
- Wheel ballast should be removed when not required. This also reduces compaction problems.
- Tyre pressures should be appropriate to the tillage operation and soil conditions.
- Generally, diesel engines operate most efficiently at an engine speed slightly above the point at which they develop maximum torque. Furthermore, wheel slippage generally decreases as speed increases. Tractors should therefore be operated at higher rather than lower speeds and at reduced throttle openings. Operators should therefore follow the maxim of “Gear up, throttle down”.

5.2.4. Programmes to Reduce Draught Power Shortage

A very important factor limiting crop production for many small and medium-scale farmers is a shortage of animal or tractor draught power. The ways in which this shortage limits crop production can be seen from the objectives of mechanisation listed in Section 5.1. The results of a draught power shortage include; a lower area than available being cultivated; a lack of timeliness; a lower quality of completed operations; and a restricted range of operations that can be carried out; all of which lead to a reduction in crop production.
A draught power shortage should be seen both in terms of conditions on individual farms as well as nationally. With regard to the former any draught power shortage needs to be considered when analysing the whole farming system. With regard to the latter the consequences of a general draught power shortage need to be considered in relation to national food security, rural development, export earnings, etc. With both of these it is very important that the main constraints to an improved draught power situation are identified and that these are tackled in a comprehensive manner. Because of the complex agricultural, social and economic implications of a draught power shortage, and its solution, it is highly desirable that a national strategy is developed and implemented to resolve the problem. Strategy formulation was discussed in Section 2.2.3 and the same principles apply here. As mentioned there, if it is not possible to develop and implement a full national strategy then it is still desirable to develop and implement specific action programmes which address the main constraints to the provision of adequate levels of draught power.

When developing programmes to overcome draught power shortages it is very important to consider the infrastructural support required, any foreign exchange implications, any changes required in traditional farming practices, e.g. animal grazing practices, etc. A full discussion is beyond the scope of this publication, but it is considered important that extension workers are aware of the logical framework and range of intervention measures that are available to address the problem, both on an individual farm basis and on a national level. Again it is emphasised that the main constraints to the provision of adequate draught power should be identified prior to the development of any intervention measures. Intervention approaches are listed below based on Elliot (1989) without further comment, and the draught power shortage is taken to include shortages of implements and operators. It also needs to be emphasised that one the most important means of reducing a draught power shortage is to reduce the draught power requirement.

Approaches to reducing a draught power and implement shortage are listed below:

A. Minimise the draught power requirements per arable hectare per year:
   1. Select energy and time efficient cultivation operations:
      - Select cultivation operations to minimise draught energy required:
        - Substitute high draught requiring operation with low or zero draught operation, e.g. replace annual ploughing with reduced tillage system.
        - Minimise the draught force required for the operation, e.g. select appropriate soil moisture conditions.
        - Minimise distance force is exerted per hectare, e.g. increase spacing of furrows or rip lines if feasible.
        - Minimise frequency of operation.
      - Select operation to minimise the time required per hectare:
        - As above.
   2. Improve implements:
      - Minimise draught force requirements for a given operation through good design.
      - Minimise time required for a given operation:
        - Increase working rate by increasing working width.
        - Increase working rate by increasing possible speed of travel.
        - Increase number of operations completed in one pass.

B. Minimise peak draught power requirements:
   1. Select crop combinations and management systems that spread the draught power requirement more evenly over the cropping season.

C. Maximise draught power availability:
   1. Increase draught power availability from existing draught animals:
1. Improve time of use of draught animals:
   - Reduce peak demand by spreading demand over the year.
   - Carry out operations when soil moisture conditions are appropriate.
   - Coordinate draught demand with condition of animal, e.g. autumn ploughing when animals in good condition.
   - Work during cooler part of the day.

2. Improve animal husbandry:
   - Improve nutrition, through improving maintenance feeding as well as supplementary feeding for work periods.
     - Improve grazing practices.
     - Produce fodder crops.
   - Improve health.
   - Improve selection of draught animals.
   - Improve operator handling of draught animals.
   - Improve training of animals.
   - Improve yokes and harnesses.
   - Match animals and power requirements of implements:
     - Sufficient animals in team for high draught force requirements.
     - Single animals for low draught force requirements.

3. Improve distribution of animal draught power between farmers:
   - Facilitate animal hire schemes:
     - Payment in cash or labour, or barter through fodder production.
   - Exchange grazing rights for use of draught animals.

4. Increase number of draught animals and improve draught power characteristics of future herd:
   - Improve nutrition:
     - Improve pastures, paddocks, fodder production.
   - Increase herd size, if practical:
     - Maximise carrying capacity of the land.
   - Breed to select desirable draught power characteristics.
   - Increase proportion of draught animals, e.g. oxen, in herd.
   - Increase use of female animals for work, with care.
   - Increase use of animals not locally commonly used, e.g. donkeys and mules.

5. Improve distribution of tractor availability between farmers:
   - Improve multi-farm use of tractors by farmers:
     - Improve machinery rings.
     - Improve cooperative services.
   - Improve contractual draught power services to farmers:
     - Improve government/private services.
     - Improve contractual services provided by large-scale farmers to small and medium-scale farmers.

6. Increase numbers of tractors:
   - Increase foreign exchange allocations, sell at realistic prices, etc.
   - Increase dealership networks.
   - Provide credit facilities, etc.
7. Increase availability of animal and tractor drawn implements:
   - Increase local manufacture.
   - Allocate foreign exchange for importation of implements not manufactured locally.
   - Improve implement sale, spares, servicing and maintenance networks.
   - Improve feedback from operators and farmers to dealers and servicing organisations.

The above outline is not exhaustive and some additional activities will be required depending on the specific constraints identified. Furthermore, the logical framework given above is not rigid and variations may be desirable for specific conditions. It must also be emphasised that the above outline does not detail the extensive infrastructure required to implement a comprehensive programme to overcome a regional or national draught power, implement or operator shortage. It is important that this should not be underestimated. This infrastructure is required to promote, manage and implement the actions listed above, which include training and extension, research and development, veterinary services, manufacture, importation, sales, servicing and maintenance, transportation, financial services, etc.

5.3. TILLAGE OBJECTIVES, OPERATIONS AND IMPLEMENTS

A brief introduction to tillage operations was given in the introduction and some of this is repeated here for convenience. Soil tillage is the mechanical manipulation of the soil within a crop production system. The overall objective of tillage is the modification of the physical, chemical and biological characteristics of the soil, so as to provide the optimum environment for the germination and development of the plants, and so enhance growth and yield. The main specific objectives of tillage are listed below, based loosely on those of the USDA Agriculture Handbook No. 316:

- To modify the soil structure by loosening and shattering the soil to increase soil aggregation and pore volume:
  - To improve the soil's aeration and water infiltration, storage and drainage characteristics:
    - To increase the soil water available to plants.
    - To reduce runoff and so reduce soil and nutrient loss due to water erosion.
    - To promote drying in some regions.
    - To reduce waterlogging problems.
  - To reduce the mechanical strength of the soil, so as to provide a suitable rooting environment which allows easy penetration of plant roots and so allows the full development of the plant root system.
  - To produce a suitable soil tilth for planting.
  - To provide a shallow surface soil mulch to reduce evaporative losses of soil water.

- To incorporate or cover crop residues, manures, fertilizers, lime to correct pH levels, herbicides, insecticides, etc., in the soil:
  - To incorporate and distribute organic matter into the soil to promote the formation of soil organic matter.
  - To incorporate and distribute plant nutrients and chemicals in the soil.
  - To partially incorporate crop residues, or totally cover them through soil inversion, so as to facilitate later mechanisation operations.

- To mix the soil:
  - To promote the incorporation and distribution of the substances listed above into the soil.
  - To mix moisture throughout a depth of soil.
  - To mix layers of soil of different textures together, to form a more desirable texture within the rooting depth or nearer the surface.
To segregate different components within the soil:
- To bring clods to the surface and bury fine soil particles to minimise wind erosion.
- To remove rocks and roots from the soil.

To establish soil configurations on the surface or in the soil profile:
- To provide the special surface configurations required for irrigation, drainage, planting in beds or on ridges, etc.
- To provide soil configurations in the soil profile, such as mole drains for drainage.

To compact or firm the soil:
- To firm the soil so as to gain good contact between the seed and soil, to promote good germination.
- To compact the soil to reduce its permeability to water, in order to make water-retaining structures such as ditches, terraces, or dams.

To control weeds and pests.

The reasons behind these objectives have been discussed fully in preceding sections. However, it does need to be emphasised again that most tillage operations have both beneficial and detrimental effects on the various parameters being considered. For example, as discussed in Section 2.1.3.4 although the incorporation of organic residues into the soil through tillage speeds up their decomposition into soil organic matter, it also speeds up the decomposition of existing soil organic matter, due to increased aeration. Furthermore, this latter effect usually outweighs the former. In dry, hot climates therefore, maximum soil organic matter content is usually achieved through zero tillage systems, with the retention of crop residues on the soil surface.

To achieve the above objectives several different tillage operations usually have to be performed. These are commonly divided into primary and secondary tillage operations. Primary tillage refers to the main, and usually deep, tillage operations undertaken between two crops to loosen the soil down to rooting depth and to prepare the land for further operations. Secondary tillage refers to those shallower operations undertaken after primary tillage to prepare the seedbed and to manage the crop. A more complete grouping of tillage operations is given below in the sequence in which they are performed for a new crop under a conventional tillage system:

a. Stubble, or post-harvest, tillage:
   Shallow tillage carried out shortly after harvest to remove weeds, and possibly cover crop residues, and to modify soil structure. This includes tillage during fallow periods for water conservation, weed control and improvement of the soil structure and fertility.

b. Primary tillage:
   Deep tillage undertaken between two crops to modify the soil structure in the main rooting area of the next crop, primarily soil loosening, to mix or incorporate crop residues, animal manures, etc., to control weeds and to prepare the land for seedbed preparation.

c. Seedbed preparation:
   Shallow tillage to prepare seedbed or to prepare for transplanting. Includes weed control and the preparation of a fairly finely granulated soil structure, to promote good seed/soil contact so as to facilitate germination and early growth. Also sometimes includes the formation of beds and ridges to facilitate harvesting of root crops or to improve soil and water conservation.

d. Crop management tillage operations:
   Shallow operations to control weeds, break up surface crusts to aid crop emergence and improve water infiltration.

Groups a, c and d above are classified as secondary tillage in the primary/secondary tillage classification system, and this system is used below for ease of description. However, this two-part classification system does suggest that tillage for a new crop starts with primary
tillage, e.g. ploughing, immediately before planting. Whereas the a. to d. grouping above emphasizes the importance of starting tillage preparations for the new crop as early as possible. In terms of tillage this can be done immediately after harvest through weed control, to reduce water loss through evapotranspiration or subsequent weed infestation, or the loosening of the surface soil structure to improve water infiltration, or the creation of a soil mulch to reduce evaporation, etc. In terms of crop production as a whole it needs to be emphasized that most preceding operations on a field will affect future crop production, especially in terms of nutrient levels and weed and pest infestation problems. The implementation of the complete sequence of tillage operations listed above may not be necessary or desirable. This will depend on the time available for the tillage operations and on other aspects of the whole crop production system.

A distinction between stubble tillage and stubble mulch tillage needs to be drawn. Stubble tillage is as defined in (a) above. Whereas stubble mulch tillage is a specific conservation tillage system in which only a small proportion of the crop residues are incorporated into the soil. The majority of the crop residues are retained on the soil surface to form a mulch to protect against erosion, soil capping and to reduce evaporation. The shallow soil tillage also produces a soil mulch to reduce evaporation and increase infiltration.

The selection of the most appropriate tillage implements for a particular situation is dependent on a number of factors. As Godwin (1990) points out no one set of tillage implements is ideal for all farming conditions. The kind, quantity, and quality of residues, the number, kind and size of weeds present, soil water conditions, soil texture, length of fallow, erosion potential, and time of operation must all be considered in selecting tillage implements. The speed and depth of tillage, width of equipment, concavity of discs, and width, pitch and angle of sweep blades are all factors in residue retention and weed control. The amount, height, and length of stubble, as well as its orientation, also influence the amount of residue buried during each tillage operation. Other important factors include the implements draught force requirement, power source availability, capital and running costs, operational characteristics under various field conditions, ease of maintenance, etc.

The effect of different primary and secondary tillage implements on soil parameters and the retention of crop residues on the surface was discussed in Section 2.2.1.3 particularly in relation to the control of water erosion. The relative effectiveness of various tillage implements in altering soil porosity, cloddiness and roughness was given earlier in Tables __ (@ Godwin 1990, p 56, fig. 2.11), __ (@ Godwin p 57 fig. 2.12), __ (@ Godwin p 57 fig. 2.13), and the effect of various tillage implements on the retention of surface residues is given in Table __ (@ Godwin p 101, table 4.1. For these various operations to be effective it is important that the soil is at the appropriate moisture contents for the operations. Tillage implements that cause excessive pulverisation of the soil should not be used on soils prone to erosion. All operations should be carried out either on-contour or only slightly off-contour, so as to provide maximum obstruction to water flow down the slope.

The main primary tillage operations include subsoiling; ploughing using mouldboard, disc, chisel or sweep ploughs; and rotary cultivation. The main secondary tillage operations include harrowing, cultivating and hoeing using harrows, cultivators and hoes with rigid or sprung tines, or discs, or various rotary soil engaging tools; compacting, using rollers; levelling, using levellers; and ridging and bed shaping using ridgers or Lister ploughs, and bed shaping implements. In-field soil moving operations which are not classified as tillage operations, but influence the effectiveness of tillage operations, include land forming, the construction of mechanical conservation works, terracing, etc. The latter operations were discussed in Section 4.

The amount of information required to be given in a full training course in the field operation of tillage equipment and the methodology of implementation, including both tractor and animal drawn equipment, and to cover all commonly encountered field conditions, is very
large and is beyond the scope of this publication. This section will concentrate on the objectives of the main tillage operations, the characteristics of the main tillage implements used to implement them and their selection and adjustment. The coverage of primary tillage equipment will be in greater depth than that of secondary tillage for the following reasons:

- Secondary tillage implements are usually of similar basic design to one of the main types of primary tillage implements, for example disc harrows are similar to disc ploughs, and chisel tine cultivators are similar to chisel ploughs. This applies both to their effect on the soil and to their basic parts.
- There is a large range of cultivating equipment and it is beyond the scope of this book to cover all of them.
- The primary tillage operations are generally the most expensive to implement, and they lay the basis for all following operations.

A brief description of the field implementation of the tillage operations will also be given. This will concentrate on ploughing using mouldboard or disc ploughs, and on ridging.

Several other publications cover tillage equipment, their operation and selection, and the field implementation of the tillage operations, and these include, FAO (1990), Krause et al (1984). Agritex (1986-1991) provides detailed course manuals for the training of extension workers in the field operation of animal and tractor drawn tillage equipment. The latter publications were produced by Agritex, Zimbabwe in collaboration with GTZ and are available for adaptation and use in other countries.

The following descriptions of the primary and secondary tillage implements are based primarily on Krause et al. (1984), as well as on FAO (1990), Lovegrove (1978), Godwin (1990) and Agritex (1986-1991). The details of ploughing methods and field layout, which are given after all the tillage implements have been described, are based primarily on Agritex (1986-1991) and Matthews and Pullen (1976).

5.3.1. Primary Tillage Operations and Implements

The main objectives of tillage were given in detail in the previous section and most of those objectives apply to primary tillage. Generally the main purpose of primary tillage is to loosen the soil and increase soil aggregation, so as to provide adequate soil pore volume in the main rooting area of the next crop. This is done to promote water infiltration, water storage and drainage, and to allow easy penetration of plant roots, as well as to provide adequate aeration. Covering of crop residues through soil inversion is important in clean tillage systems. Only partial incorporation of crop residues is important in stubble mulch systems. Incorporation of organic and inorganic materials in the soil, and the control of weeds and pests are generally important. Crumbling, i.e. increasing the proportion of loose soil aggregates, and mixing are important, especially in areas where the following crop has to be sown shortly afterwards and several secondary tillage operations cannot be carried out. Primary tillage is a more aggressive and deeper operation than secondary tillage, and often leaves the soil surface rough, although smooth surfaces are possible.

The main primary tillage implements are the mouldboard, disc, chisel and sweep ploughs; the rotary cultivator; the paraplough; and the subsoiler. The sweep plough is a specialised implement generally used only in dryland farming systems. The ways in which tillage implements alter the condition of the soil can be divided into the following categories; they pulverise, loosen, mix and invert the soil. The predominance of these different effects in the action of the main primary tillage implements are given in Figure ___(@ Krause p 74, fig 17). Any tillage operation combines these effects and each of these effects may be desirable or undesirable depending on the required end result. This in turn depends on the climatic region, i.e. humid or arid, etc., erosion potential, soil type, weed and pest infestation potentials, crop type, etc. As discussed in the previous section these different tillage effects are the main characteristics of the various implements to be considered when selecting the most appropriate
tillage implement to carry out a specific tillage operation. Other important factors include the implements' draught force requirement, power source availability, capital and running costs, operational characteristics under various field conditions, ease of maintenance, etc. Some of these characteristics will be discussed under the headings of the implements discussed.

On small farms reliant on animal drawn power the main primary tillage implements used are the mouldboard plough and the single tined chisel plough. On medium scale farms with access to tractor power the mouldboard, disc and chisel ploughs and one or two tined subsoilers are in common use. However, on both small and medium-scale farms which use contractual ploughing services, or cooperatively own tractor and tillage equipment, then all the main primary tillage implements listed above may be used, and for this reason are all described in some detail in the following sections.

5.3.1.1. Mouldboard Ploughs

A range of tractor drawn and mounted and animal drawn mouldboard ploughs are shown in Figure ____(@ FAO Manuals + AGRITEX AP2, p 2.2, fig. 2.1.). The function and characteristics of the mouldboard plough will first be described, followed by a description of its parts and operation.

Although the mouldboard plough is a simple implement with no moving parts, there is a wide choice of designs for its components that are suited to different soil and operational conditions. Furthermore, knowledgeable selection and good maintenance of these components is important if the plough is to be used efficiently. This is particularly important for low draught power sources such as animal draught, as it crucially affects both the work rate and the quality of the ploughing. It is also important for high draught power sources where the correct selection and maintenance of the plough is very important both for the quality of the work and the fuel efficiency of the tractor. Because of these factors, and its common use, the mouldboard plough will be discussed in more detail than the other primary tillage implements.

A. Function and Characteristics

The mouldboard plough cuts, breaks, loosens and inverts the soil. As shown in Figure ____(@ Krause 1984, p 80, fig. 19) the plough body cuts, both vertically and horizontally, a slice of soil whose height and width are in the ratio of about 1:1.5 to 1:1. The slice of soil is lifted, moved upwards along the mouldboard and turned over an angle of 120 to 150 degrees, depending on the height to width ratio of the slice. The lifting, compacting, bending and turning process causes the slice to rupture both along its length and laterally. The free fall which follows breaks up the soil even more. The degree of pulverisation and loosening of the soil slice depends upon the shape of the plough body, the working speed, type of soil, and the soil moisture conditions. Material on the surface of the soil is deposited in strips on the bottom of the furrow and on the sides of the slice.

There are two basic types of mouldboard plough, the one-way and the reversible plough. The one-way plough turns the furrow slice to one side only whereas the reversible plough can turn the furrow slice to either side, and the implications of this will be discussed later.

The mouldboard plough is used for the following purposes:

- Stubble tillage.
- Deep inverting tillage.
- Mechanical weed control.
- Working in organic matter.
- Seedbed preparation.
- Wasteland cultivation (reclamation).
The mouldboard plough was developed over a long period primarily for use in the temperate climatic zones. As shown in Figure ___(@ Krause 1984, p 74, fig 17 + ) it has very good inverting and loosening effects on the soil. Due to its effect of completely inverting the soil it has very good weed control properties and this is one of its main desirable attributes. It is also a strong and simple implement and only a few of its parts are subject to wear.

However, in arid and semi-arid regions the complete inversion and increased aeration of the soil produced by this plough results in high moisture loss and the rapid decomposition of soil organic matter. These are very serious disadvantages and need to be balanced against its good weed control properties. Further disadvantages of the plough include a high draught power requirement, low working rate, and the intensive secondary tillage needed to break up the large clods after primary tillage to prepare a suitable seedbed.

B. Description and Operation

The plough body parts will first of all be described, followed by descriptions of the reversible/non-reversible plough body arrangements, and then the attachment of the plough to the draught power source.

The mouldboard plough is shown in Figure ___(@ Lovegrove 1978, p 3, fig. 1) and it consists of the share, mouldboard, tailpiece, landside, frog, beam and a coulter mounted on the beam. These are described below:

Share:

The share makes the horizontal cut which severs the slice of topsoil from the subsoil. The share is attached to the frog and is subject to high continuous and impact loads and to high frictional wear. Good quality shares are made of three-ply steel with outer layers of frictional wear resistant high carbon steel and a centre layer of impact absorbing low carbon steel. Some shares consist of two or three parts, namely the point, wing and shin. These are shown in Figure ___(@ Krause 1984, p 84, fig 21 and Lovegrove p 6 fig 5). Krause et al (1984) lists the following main types of shares:

- **Trapezoidal:**
  For light soils and straight cuts. The point is reinforced to allow resharpening and reforging.

- **Pointed:**
  For medium to heavy soils. This share is better than the trapezoidal shape for breaking up the soil, penetration, support, resistance to wear and susceptibility to damage from stones. It can be resharpened and reforged.

- **Gunnel-type:**
  The share point and cutting edge are supported by a vertical, V-shaped flange. This flange is also used to provide extra material for forging. This share is very rigid and resistant to wear and suitable for difficult conditions.

- **Chisel Point:**
  For very heavy or stony soils, this share is similar to the pointed one except that, instead of the forgeable point, it has a chisel that can be adjusted as it wears and also used on both sides.

- **Disposable:**
  This self-sharpening share is suitable for light to medium heavy stoneless soils. It is not forgeable as it is narrow and thin.

In order to ensure that the plough has good penetration and stability the share is designed to slightly overlap the landside plate both vertically and laterally to provide a downwards force and also a sideways force into the unploughed land. These parameters are
defined below and their measurement is shown in Figure ___(@ AGRITEX, AP 2, p 2.16 and 2.17 fig. 2.15 and 2.15):

- **Suction, or pitch:**
  Suction is the protrusion of the share below the landside. The landside travels along the bottom of the furrow. Unless the share protrudes below the landside the plough body cannot dig into the soil to achieve the required ploughing depth.

- **Land suction, or lead to land:**
  Land suction is the protrusion of the share and the shin of the mouldboard into the unploughed land over the landslide. This enables the plough to cut into the soil and maintain a furrow slice of the required width.

The manufacturer should specify the acceptable range of the above values for their ploughs and these are usually in the range of 10 to 20 mm. As the share wears these values are decreased leading to poorer penetration. If worn shares are not replaced then in order to achieve the required penetration the plough has to be "badly" adjusted which leads to a higher draught force requirement and greater difficulty in its handling. Some shares on animal drawn ploughs need to be replaced after ploughing only 2 ha in abrasive soils.

Other important parameters are defined below and their measurement is shown in Figure ___(@ Krause 1984, p 85, fig. 22):

- **Share point angle:**
  The angle between the lower share edge and the direction of travel, usually 20 to 35 degrees.

- **Share lift angle:**
  The angle between the furrow bottom and share, perpendicularly to the edge, usually 35 to 50 degrees.

For both of the above wide angles are suitable for light soils or low speeds, e.g. animal draught, but narrow angles are more useful for heavy soils or high speeds. The different share shapes and angles should always be compatible with the shape of the mouldboard.

**Mouldboard:**

The mouldboard turns the furrow slice through approximately 135 degrees to lay it against the preceding slice. It is mounted on the frog and is often also supported by an angle strut connected to the beam or frame. Good quality tractor drawn mouldboards are made of three-layered steel laminate with very hard wear resistant outer layers and a shock absorbent low carbon steel central layer. The shin of the mouldboard is frequently replaceable as it is the most hard wearing part, especially if no coulter is used. The design of the mouldboard is important for its scouring qualities, i.e. its freedom from soil adhesion to the friction surface, and for the type of work that it produces. The curvature of the mouldboard combined with the various positions of the share gives a range of shapes. The choice of these for a particular job depends on the soil type, topography, the required inversion and the operating speed. Several different systems are used to classify the basic shapes of plough bodies, and one of these together with their uses, is shown in Figure ___(@ Krause 1984, p 86, fig. 23):

- **Steep:**
  For light, sandy soils, little inversion, low speed.

- **Steep, short:**
  For light, sticky soils, little inversion, low speed.

- **Medium steep:**
  For medium soils, average inversion, average speed.

- **Inclined:**
  For medium and heavy soils, average to pronounced inversion, average to high speeds.

- **Helical:**
  For heavy slaked soils, almost complete inversion, average to high speeds.

- **Universal:**
For all soil types except extremes, average inversion, average speed.

- Spiral:
  For the heaviest soils, complete turning of the slice, high speed, also suitable for sloping soils.
- Slatted:
  For very sticky soils.

Another classification system has the following classes, based on the depth to width ratios of the mouldboard plough; the general purpose, semi-digger base, digger base and the deep digger base.

The shorter and more concave the plough, the larger the share point angle and the higher the speed of operation the more aggressive is the plough's action on the soil, resulting in more shattered and less well defined furrow slices. Generally, the more shattered the soil the more suitable it is for immediate planting. Where good packing of the furrow slices is important, for example when ploughing grassland or clover ley, then a slow-turning mouldboard producing well defined unbroken furrows is desirable.

Tailpiece:

The tailpiece is used to improve the inversion and crumbling of the soil. It is mounted on the upper section of the mouldboard and can be adjusted to the ploughing depth.

Landside:

The angular arrangement of the share and mouldboard in relation to their direction of travel causes a side-thrust on the plough. The landside plate is fitted to each plough body on the opposite side to the mouldboard to convey this force to the furrow wall and so counteract the force, enabling the plough to travel in a straight line. On a multi-furrow plough the front and any intermediate landside plates are shorter than the rear one to give clearance between the bodies. On some ploughs an obliquely mounted rear wheel is fitted to counter this side-thrust.

The landside plate also exerts a downwards force on the furrow bottom, either because of the design of the plough or because of changing soil conditions within the field, and this results in wear. To allow for this many landsides are reinforced on their underside with a steel or iron pad known as a slade or heel-piece. Excessively worn landsides lead to difficulty in correctly adjusting and handling the plough.

When ploughing under wet conditions on soils with a sizable clay content the forces on the landside acting on the furrow bottom can result in smearing which leads to compaction and impermeable layers being created.

Frog:

The frog is a robust steel or malleable iron casting to which the share, mouldboard and landside plate are attached. The soil engaging parts of the plough convey the draught forces to the beam through the frog. In some makes a limited amount of adjustment can be made in relation to its supporting beam or leg. This is usually referred to as individual pitch adjustment.

Body:

The term plough body applies to the complete assembly of the frog, share, mouldboard and landside plate. It is the design of this assembly that is of the greatest significance when selecting a plough, since it determines the type of work the plough will produce.

Beam:
The beam connects the plough body to the draught power source, via the chain for animal draught or via the cross shaft and three-point linkage system for tractor draught. Sometimes the beam is curved to carry the plough bodies, in other cases they are horizontal and carry vertical legs, or shanks, to support the bodies. On tractor drawn ploughs protection against overloads due to the plough impacting rocks or roots is often provided. These range from shearbolts to fully automatic mechanical, hydraulic or pneumatic systems. The automatic "stump-jump" systems prevent the plough body or shank from breaking and permit uninterrupted operation.

Coulter:

The coulter is a front mounted tool that makes the vertical cut which severs the furrow slice from the unploughed land. Many mouldboard ploughs, and especially animal drawn ploughs, do not use a coulter and the vertical cut is then made by the share and the mouldboard. Some of the standard coulters are shown in Figure ___(@ Krause p 87, fig. 24). Knife coulters are simpler and lighter in weight than disc coulters but have a higher draught force requirement. A skim coulter, or jointer, which looks like a small mouldboard plough, is also sometimes used and is positioned close to the line taken by the disc or knife coulter. Its object is to chamfer off a narrow strip of surface vegetation from the left-hand corner of the furrow slice before it is inverted, to improve the inversion of weeds and to discourage the growth of weeds between the furrows, and to seal the furrow joints. The manure feeder coulter is used to cleanly bury manure. Coulters are usually mounted on the beam but some are mounted on the plough body.

The following adjustments to coulters are based on Krause et al (1984):

- Knife coulter:
  0-30 mm in front of, 10-30 mm on the side towards the unploughed land, and approximately 25 mm above the point of the share.
- Disc coulter:
  As deep as possible with the axis 50 mm above the soil surface, 10-20 mm on the side towards the unploughed land.
- Skim coulter:
  Small angle of attack, 40-80 mm deep, 10-20 mm on the side towards the unploughed land, and 250 mm in front of the point of the share. The width is generally 0.3-0.7 times the width of the plough body and the depth is 0.3-0.5 times the depth of the plough body.

One-way and reversible ploughs:

There are two basic types of mouldboard plough, the one-way and the reversible plough. The one-way plough turns the furrow slice to one side only, whereas the reversible plough can turn the furrow slice to either side. Care should be taken in the use of the names as the same names are given to the opposite types of plough in Europe and the USA. The names used below are those advocated by FAO:

- One-way ploughs:
  Equipped with plough bodies that turn the furrow slice to one side only, usually to the right. The main advantages of this type are their greater simplicity and lower cost, and for high powered tractors that a large number of plough bodies can be used. Their main disadvantages are that more complicated ploughing systems are required, including the careful layout of the field in lands, unevenness due to the creation of opening and closing furrows, and ploughing on-contour is more difficult.
- Reversible ploughs:
  Equipped with two sets of bodies mounted symmetrically on a shared frame that can be rotated along the longitudinal axis. This arrangement makes it possible to turn the furrow slice towards the same side of the field even though the plough travels in
opposite directions. The bodies can be swivelled mechanically or hydraulically on tractor drawn ploughs. Their main advantages include a high operational efficiency, laying out of fields in lands is not necessary, a level surface can be created, which is important for irrigation and drainage purposes, and contour ploughing on slopes is possible. Their main disadvantages include higher cost and weight, swivelling mechanism subject to wear, and their greater weight limits the total number of plough bodies that can be used. Reversible ploughs require one or two extra hydraulic connections, depending on the type of hydraulic cylinder used in the swivel mechanism.

Linkage systems and depth and width adjustment for tractor draught power:

The headstock and hitch bar, or cross-shaft are used to attach the plough to the 3-point hitch system of the tractor. The headstock and brace provides the hitch point to connect to the top link. The cross-shaft is a steel shaft positioned at the extreme front of the plough and arranged at right angles to the beams. On non-reversible ploughs each end is cranked and machined to provide attachment points for the tractor's lower links. The cranks are diametrically opposed so that as the shaft is rotated the plough may be angled to cut either a wider or narrower front furrow. This is provided to correct minor discrepancies of front-furrow width, and should not be used as the main means of adjusting the front furrow width, which is done by adjusting the wheel spacing.

There are three standard pin dimensions and lift linkage geometries for the connection of implements to the 3-point linkage systems of tractors. These are termed the hitch categories and it is important that the implement is correctly matched to the tractor. The hitch categories are based on the power of the tractor and the power requirements of the implements, as given below:

- **Cat I** - Tractors up to 35 kW
- **Cat II** - Tractors 35 to 70 kW
- **Cat III** - Tractors above 70 kW

There are three ways in which ploughs can be linked to tractors:

- **Mounted ploughs:**
  One to five plough bodies on a frame are mounted on the tractor's three-point hitch system. Quick coupling systems can be fitted. Tractors with free-link operation of the hitch system can carry the plough during transport and support it by a gauge wheel when it is in operation. With automatic depth or draught control the plough is never supported by wheels. During ploughing with this latter system the weight of the plough and a large part of the forces acting on the plough are transferred onto the rear wheel of the tractor. This increases the tractive force capable of being exerted by the tractor and reduces slippage. However, it also reduces the weight on the front steering wheels and care should be taken that this is within acceptable limits.

- **Semi-mounted ploughs:**
  Four to eight plough bodies on a frame are hitched at the front to the three-point hitch system and supported at the rear by a furrow wheel which is often hydraulically operated. This mounting method prevents too much weight being taken from the tractor's front axle, as occurs in heavy ploughs with a wide clearance between the bodies, and also allows more plough bodies to be used than with mounted ploughs.

- **Drawn or trailer ploughs:**
  These are linked to the hitchbar and are fitted with wheels to control their depth. A large number of plough bodies on a frame can be attached and they produce only a small additional load on the tractor's rear axle. Their in-field manoeuvrability is much lower than mounted ploughs and this causes problems on small fields. They can only be transported between fields at low speeds.
The draught force sensor for the automatic depth or draught control system is provided on either the upper or lower links, depending on the make and model of the tractor. When in operation the control system slightly raises and lowers the plough, depending on soil and terrain conditions, to provide a fairly uniform draught power requirement on the tractor. Only under uniform soil conditions, with a level or undulating surface, does the control system produce ploughing to a uniform depth. The power required to lift the plough from the soil during operation is high and is about three times the weight of the plough, (Krause et al 1984).

Adjustments for working depth:

- The plough frame should be completely level, both in the direction of travel and laterally, during ploughing to ensure that all the plough bodies work at the same depth. For the 3-point hitch system this adjustment is made by altering the length of the upper link and one of the lower link lift arms.
- Mounted ploughs:
  - Adjust hydraulic system or upper link for free floating action.
- Semi-mounted ploughs:
  - Adjust lower links and depth wheel.
- Trailer ploughs:
  - Adjust depth wheels.

Adjustments for working width:

- The plough's working width is determined principally by the number of bodies and the cutting width of each body. On some ploughs the working width can be altered by adding or removing plough bodies, or by altering the location of the plough bodies on the frame.
- It is very important that each furrow slice is the same width, otherwise an uneven surface will be produced. The first furrow width is adjusted by means of altering the wheel spacing until the first furrow width is the same width as the succeeding furrows. On non-reversible ploughs the cranked cross-shaft can also be used to make minor secondary adjustments to the width of the first furrow slice.

Check chains are used to prevent excessive lateral movement of the plough, especially during transportation. Without their use the tractor tyres and linkage system can be damaged. During operation with a correctly adjusted plough the check chains should be slack most of the time.

Linkage systems and depth and width adjustments for animal draught power:

There are three main types of animal drawn mouldboard ploughs categorised according to their linkage system. These are the beam plough, and two types of chain-pulled ploughs, the swing plough and the wheeled plough, as shown in Figure ___(Inns, Ag Eng Spring 1990 p 13, fig. 2). Beam implements are the most common in the Near, Middle and Far East whilst chain-pulled ploughs are almost universally used south of the Sahara.

Beam implements are inherently more stable than chain-pulled ones and are usually controlled by one hand, whilst two handles are usually fitted for the control of chain-pulled implements. A swing plough has no depth control wheel, although it may have a small nose-wheel or steadying wheel fitted at the front of the ploughbeam, which is used mainly to assist in the handling of the plough. The wheeled plough normally has two or more wheels of relatively large diameter whose main purpose is to assist in depth control by supporting a significant proportion of the plough's weight.

The mechanics of animal drawn cultivation implements are described in detail by Inns (1990) and only a brief overview is given here. For beam implements the angle of the plough body can be adjusted relative to the angle of the beam. This is for depth control and to allow for variations in the height of the attachment to the yoke or harness for draught animals of
different height. As the angle between the plough beam and the plough body is increased so the depth at which the plough will operate increases. Depth control should not be achieved through applying an upwards or downwards force on the handle as this will tire the operator, and the plough will not be operating in its ideal position.

For chain drawn ploughs a slightly more complex system is used. The hitch assembly, see Figure (AGRITEX, AP 2, p 2.19 fig. 2.18) allows the hitching point to be moved, thus regulating the depth and width of ploughing. The steadying wheel allows greater control of the plough by the operator, and should not be used as the prime means to control depth. Details of two different types of hitch assembly are shown in Figure (AGRITEX, AP 2, p 2.24 and 2.25, figs. 2.22 and 2.25). The depth clevis allows the hitch point to be altered vertically so as to change the depth of the plough. The cross clevis allows the hitch point to be altered laterally so as to alter the width of cut.

In order to understand how the plough reacts to different hitch point settings it is useful to imagine that all the soil forces acting on the share and mouldboard can be summed up into one force acting at one point on the mouldboard. The direction of the imaginary single force acting on the plough and the point at which it acts are such that the behaviour of the plough remains unchanged. This point is called the centre of pressure and the force is called the resultant force. The centre of pressure at normal working depth is roughly a third of the way up from the furrow bottom to the soil surface, i.e. roughly at the point where the share joins the mouldboard, and roughly one third of the length of the share away from the share point. If the steadying wheel is not exerting a force on the soil then, under operating conditions, the position of the hitch point and the line of the chain is such that an imaginary straight line could be drawn along the chain extending it to the centre of pressure, as shown in Figure (AGRITEX, AP 2, p 2.19 fig. 2.18). From this it can be seen that as the hitch point is raised so the depth of the plough increases. And as the hitch point is moved to the right, on a plough body that turns the furrow slice to the right, so its width of cut increases.

The length of chain and the height of the yoke to which it is attached determines the angle of the chain at the hitch point. From the above it can be seen that this in turn affects the hitch adjustment for a specific depth. The same applies to a chain connected to the swingles or evener of a harness system. It is important that the length of chain used is such that the depth clevis is set to roughly its mid-position for average soil conditions so that higher and lower settings can be made for harder or softer soil conditions. It is also important that too short a chain is not used as this will bring the plough so close to the animals that it may injure their back legs. A chain used with yoked oxen of around 500 kg in weight, and for average soil conditions, is typically 2.9 m in length and the following adjustments can be made:

- A longer chain is needed if the soil is very hard, or the draught animals are taller than average.
- A shorter chain is needed if the soil is very soft, or the animals are very short.

For ploughing with cattle or water buffaloes short yokes are used, the length being determined by the size of the animals and the minimum width that allows the animals to operate without interfering with each other’s movements. A plough yoke for animals of roughly 500 kg has a distance of 80 to 90 cm between the centres of the skeis. This allows for ploughing up to the full width of cut within the range of settings on the hitch assembly. A longer yoke, such as the cart or cultivator yoke, moves the hitching point away from the furrow and makes it impossible to set the plough for the required width.

As laid out in Agritex (1986-1991) the following procedure should be followed when setting the swing plough:

- Raise the steadying wheel as high as possible or remove it.
- Set depth by adjusting depth clevis until required ploughing depth is maintained.
- Lower steadying wheel to just touch the ground when the plough is at operational depth.
- Set width of cut by adjusting the cross clevis.
- Try out and re-adjust if necessary. If the range of the hitch assembly does not achieve the required depth or width of ploughing, then check that the chain and yoke are the correct length and size respectively.

The following procedure should be used when adjusting the wheeled plough:
- Place the plough on a flat surface with the landside parallel to the surface.
- Adjust the wheels so that they are at a height equal to the required plough depth by placing blocks under them.
- Adjust depth clevis to central position.
- Set width of cut by adjusting the cross clevis.
- Try out in field and note position of the heel of the landside.
  - If the heel severely gouges the furrow bottom then raise the point of attachment of the chain on the depth clevis.
  - If the heel does not slide on the furrow bottom unless the operator holds the handles down then lower the chain on the depth clevis.

With a correctly adjusted share and landside the plough beam should be parallel to the soil, and the handles level, when in operation. Only a light touch on the handles of the plough should be required from the operator to maintain balance so that most of the attention can be given to direct the draught animals. Good work is shown by uniform level furrows, completely inverted, burying all weeds, and with flat, level, furrow bottoms. Ploughing methods and field layout will be described in Section 5.3.4.

Power and Draught force requirements, sizes and work rates:

Tractor draught power:

The following technical details are based on Krause et al (1984):
- Working width per body: Up to 42 cm.
- Working depth: Up to 35 cm (more for special ploughs).
- Number of bodies: Up to 12, or 24 for reversible ploughs.
- Frame height: Up to 90 cm.
- Clearance between bodies: Up to 110 cm.
- Weight: Up to 310 kg per body.
- Overload devices: Protection against rocks, etc., by means of shearbolts, helical springs, hydraulic and pneumatic cylinders, overload protection on mountings.
- Speed of operation: 5 to 8 km/h.
- Power requirements: 15 to 25 kW per body.
- Work rates: Speed (km/h) x width/10 (m) ha/h.
  Effective capacity at 5.5 km/h is 0.4 ha/h per metre of width.

(Note: The work rate given by the equation: Speed (km/h) x width/10 (m) ha/h, does not take account of headland turning time).

Animal draught power:

The draught force requirements of a plough depend on the condition and characteristics of the plough, the soil conditions, and the depth and width of cut. Typical draught force requirements for a single furrow plough with a depth of cut of 200 mm and a width of cut of 250 mm, vary from roughly 1.2 to 1.7 kN depending on soil conditions. For a working speed of 0.8 m/s (2.88 km/h) this leads to a power requirement of roughly 1 to 1.4 kW.

The work rates measured in trials are highly variable, depending on soil condition, depth of ploughing, width of share, quality of ploughing, etc., and Matthews and Pullen (1975) give rates varying from 10 to 23.3 hours per hectare. For a furrow slice width of 250 mm and a
speed of 0.8 m/s the theoretical time required to cover a hectare would be 13.9 hrs. excluding headland turning time. Allowing 10% of the time for headland turning time this theoretical value increases to 15.3 hrs, excluding rest periods. When faster work rates than the theoretical are measure in the field this is usually because a wider cut than the share width is being made. This results in an uneven tilled depth.

5.3.1.2. Disc Ploughs

A range of tractor drawn disc ploughs is shown in Figure ____ (Photographs + @ FAO Manuals - Disc ploughs). The function and characteristics of the tractor drawn disc plough will first be described, followed by a description of its parts and operation. Animal drawn disc ploughs have generally not been developed on a commercial basis as they are heavier than mouldboard ploughs and the central bearing and disc control mechanism is expensive to manufacture.

The disc plough, disc tiller and disc harrow are basically of similar design. The disc plough is a heavy implement, made up of 2 to 12 discs, designed for deep primary tillage and the discs are designed to throw the soil in only one direction at a time. The resultant side force is counteracted by a furrow wheel. Disc harrows range from heavy to light implements and are used for shallow primary tillage or secondary tillage. They are equipped with rows of discs that throw the soil in opposite directions. The disc tiller is intermediate to a disc plough and a disc harrow, consisting of a 10 to 40 discs, but only throwing the soil to one side. They are used for shallow primary tillage or secondary tillage and its usual application is in dry locations.

The function and characteristics of the disc plough, and the disc harrow and disc tiller where these overlap, will first be described, followed by a description of their parts and operation. The disc harrow and disc tiller are further described in the section on secondary tillage implements.

A. Function and Characteristics

The disc is rotated by the soil forces acting on the disc and it tears, lifts, rolls, loosens, mixes and partially inverts the furrow slice. Unlike the mouldboard plough the disc plough will not penetrate into the soil of its own accord and it requires the weight of the disc and heavy frame for penetration. Additional weights may also need to be added.

The disc plough is generally used for the same purposes as the mouldboard plough. There is relatively little difference between the mouldboard and disc ploughs in terms of their effect on the soil, maintenance, reliability, power requirements and total tillage costs. However, the limited differences may be important for specific situations. The differences between the two in their effect on the soil was shown in Figure ____ (@ Krause 1984, p 74, fig. 17). Krause et al (1984) lists the following advantages and disadvantages of the disc plough over the mouldboard plough:

Advantages:
- Only partial inversion of the soil so that plant residue is left on the surface, thus reducing the erosion risk and water losses by evaporation.
- Mixing action on loose soils.
- Rolls over obstacles so that hardly any breakage occurs.
- Lower risk of choking, e.g. for sugarcane, cotton, maize.
- Fewer problems with sticky soils.
- Hardly any smearing of the furrow bottom, as compared to the smearing caused by the landside heel of the mouldboard.
- The wear is spread over the entire circumference of the disc.
- The discs are self-sharpening.
Disadvantages:
- Penetration is difficult in hard soils.
- Heavy weight and hence higher prices.
- Greater lifting capacity required for tractor’s hydraulic system.
- Furrow wheel is needed for controlling depth and lateral movement.
- Not usually suitable for slopes owing to the strong lateral forces.
- The ploughs weight may cause compaction of the furrow bottom.
- Less efficient weed control because of only partial inversion of the furrow slice.
- Soil surface is not as level after ploughing, which is especially important in irrigated fields.
- The rotating action of the disc in cohesive soils may produce deposits of clods and these may be difficult to crumble by secondary tillage operations.

Generally, disc ploughs are more suitable than mouldboard ploughs for use in hard, dry soils, sticky soils, hardpans, highly abrasive soils, and in soils containing heavy roots or rocks. On dry, heavy soils penetration can be achieved only with a suitable high load of up to 500 kg by adding weights. It should also be noted that large discs require less draught and cut through plant residues more satisfactorily than small discs. Discs with scalloped edges are used to cut through heavy crop residues.

The disc plough is used mainly in the tropical and subtropical regions. Some considered it to be more suitable for use than the mouldboard plough in regions with a high risk of erosion, as it does not completely invert the soil, and because it also leaves approximately 50% of the plant residue on the surface, see Figure ___(@ Godwin 1990, p 101, Table 4.1). However, others point out that the rolling action of the discs has a more abrasive action on the soil than the mouldboard resulting in a higher proportion of fine soil particles that are more prone to erosion than large aggregates.

Although the disc plough does not result in the complete inversion of the soil, its action on the soil still results in a high moisture loss and the rapid decomposition of soil organic matter, although to a lesser extent than the mouldboard plough. The poorer weed control characteristics of the disc plough may also result in greater evapotranspiration losses than the mouldboard plough. Its use in arid and semi-arid regions should therefore be selected with care. Together with the mouldboard plough it also shares the disadvantages of a high draught power requirement, low working rate, and intensive secondary tillage needed to break up the large clods after primary tillage to prepare a suitable seedbed.

B. Description and Operation

Disc ploughs are very heavy implements equipped with between one and twelve concave discs. Each disc is mounted on its own shank with a bearing and frog, which allows the disc to rotate and its lateral and vertical angle to be altered for different soil conditions. The shanks are mounted on a sturdy steel frame diagonally to the direction of travel. The hitch bar and headstock are similar to those used on the mouldboard plough. The disc plough is shown in Figure ___(@ Krause 1984, p 92, fig. 27) and its various parts, and their adjustments are described below:

Disc:

The disc tears rather than cuts the furrow slice, then lifts rolls, mixes and inverts it. The action of the soil on the disc rotates it, and this plus its angle of travel allows the disc to roll over obstacles. The discs are made of specially treated manganese steel that is very resistant to wear. The hardness is comparable to that of plough shares and may be as much as 600 HV (Vickers Hardness). The diameter of the disc ranges from 560 to 810 mm, and their thickness from 5 to 8 mm. The larger diameter discs are used for deeper ploughing and normal working
depth is 25 to 40 cm. The discs' concavity is defined as the depth of the centre in relation to the edge, and is between 60 to 120 mm. As the discs' concavity increases so does its mixing action and its draught force requirement, while the lateral forces produced are decreased.

The disc angle and tilt angle are defined in Figure ___ (@ Krause p 95, fig. 29). The angles are adjusted on the frog bearing and should be adapted to the soil conditions as given by Krause et al (1984):

<table>
<thead>
<tr>
<th>Soil</th>
<th>Tilt angle (vertical) Degrees</th>
<th>Disc angle (horizontal) Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard</td>
<td>3 - 20</td>
<td>45 - 50</td>
</tr>
<tr>
<td>Cohesive</td>
<td>10 - 25</td>
<td>43 - 48</td>
</tr>
<tr>
<td>Loose</td>
<td>15 - 30</td>
<td>40 - 45</td>
</tr>
</tbody>
</table>

The disc angle can be adjusted on every plough, whereas the tilt angle cannot always be adjusted. When the disc is tilted, it is important that the front cutting edge is deeper than the chamfered rear of the disc, otherwise the discs' tearing action will be converted into a cutting action and this may result in the smearing of moist soil. This angle of clearance is shown in the above figure. In addition to this the wider the tilt angle, the less freedom is left for the disc angle, as the back of the disc may then scour against the furrow wall. This would result in increased wear and a greater power requirement.

Penetration is improved by adding weights to the plough and by increasing the disc angle. The larger the disc angle, the smaller the tilt angle, the more concave the disc, and the higher the speed of operation the more aggressive is the plough's action on the soil, resulting in more shattered and less well defined furrow slices. Generally, the more shattered the soil the more suitable it is for immediate planting. Where good inversion and packing of the furrow slices is important, for example for good weed control or the burial of crop residues, then a less aggressive action is required to produce well defined furrows.

Scraper:

Scraper shaped like hoes or small mouldboards remove the soil from the disc and improve the inversion. When used in non-adhesive soils with few weeds or residues the scrapers are sometimes left off. For maximum inversion their correct adjustment is important.

Frog, bearing and shank:

Each disc is mounted on a bearing housed within the frog. The bearing is required to allow the disc to rotate. A tapered roller bearing is used which is adjusted by a castle nut to prevent excessive play. The frog is designed to allow adjustments to the tilt and disc angles as described above. The frog in turn transmits the forces from the disc to the vertical shank that is mounted on the frame.

Furrow wheel:

The rear furrow wheels are used to counteract the lateral forces that result from the disc operating at an angle. The furrow wheels are angled at up to 45 degrees from the surface and are equipped with a collar. The wheel is sprung and its adjustment is determined by the depth of ploughing and the hardness of the soil.

One-way and reversible ploughs:

Disc ploughs can be made with only one set of soil engaging tools, as opposed to the
two sets required for mouldboard ploughs, because the discs are symmetrical. The discs are mounted on a sub-frame, which is attached to the main beam by a pivot near its centre to allow rotation through an angle of 30 to 40 degrees, either manually or hydraulically. To keep the same disc angle for both ploughing directions a lever system is used to rotate the shanks of the individual discs through a small angle when the sub-frame is rotated. At the same time a second system of levers reverses the rear furrow wheel.

The advantages and disadvantages of one-way and reversible disc ploughs are similar to those for the mouldboard plough.

Linkage systems and depth and width adjustment for tractor draught power:

The linkage systems for the disc plough are basically the same as for the mouldboard plough. Some minor differences exist with regard to adjustments due the requirement of a furrow wheel on the disc plough to counteract the lateral forces. The adjustment of this sprung wheel is partly dependent on the depth of ploughing. Mounted ploughs are equipped with a rear furrow wheel. Trailer disc ploughs are equipped with a land wheel attached to the rear lifting mechanism and a front and rear furrow wheel.

Adjustments for working depth:
- The plough frame should be completely level, both in the direction of travel and laterally, during ploughing to ensure that all the plough bodies work at the same depth. For the 3-point hitch system this adjustment is made by altering the length of the upper link and one of the lower link lift arms.
- The working depth is maintained mainly by the weight of the plough. The disc and tilt angles also strongly influence the depth control and should be adjusted to suit the soil condition as described earlier.
  - Mounted ploughs:
    - Adjust hydraulic system or upper link for free floating action and furrow wheel
  - Semi-mounted ploughs:
    - Adjust lower links, and the depth and furrow wheels.
  - Trailer ploughs:
    - Adjust depth and furrow wheels.

Adjustments for working width:
- The plough’s working width is determined principally by the number of discs and the size of each disc. On some ploughs the working width can be altered by adding or removing discs, or by altering the location of the discs on the frame.
- Adjustments can also be made to the angle between the main frame and the 3-point headstock. The cutting width of each disc can also be changed by altering the disc angle. On reversible ploughs this can be achieved by altering the degree of sub-frame rotation.
- It is very important that each furrow slice is the same width otherwise an uneven surface will be produced. The first furrow width is adjusted by means of altering the wheel spacing until the first furrow width is the same width as the succeeding furrows. On non-reversible ploughs the cranked cross-shaft can also be used to make minor secondary adjustments to the width of the first furrow slice.

Power and Draught force requirements, sizes and work rates:

The following technical details are based on Krause et al (1984):
- Number of discs: 2 to 12.
- Diameter of discs: 560 to 810 mm.
- Working width:
- Working depth: 20 to 40 cm.
- Frame height: 65 to 80 cm.
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- Clearance between discs: 50 to 75 cm.
- Weight per disc: 150 to 250 kg.
- Overload devices: Not required.
- Speed of operation: 5 to 8 km/h.
- Power requirements: 15 to 20 kW per body.
- Work rates: Speed (km/h) x width/10 (m) ha/h. Effective capacity at 5.5 km/h is 0.4 ha/h per metre width.

5.3.1.3. Chisel Ploughs

A range of chisel ploughs, both tractor drawn and mounted, and animal drawn, are shown in Figure ___ (Photographs + @ FAO manuals). The original animal drawn plough, the ard, was the forerunner of the chisel plough and present day decedents of the ard are commonly used in North Africa and Asia. In India and Pakistan they are called Desi Ploughs. In Southern Africa a chisel tine is commonly fitted to the standard animal drawn plough beam and is called the ripper tine.

Subsoilers, chisel ploughs and cultivators are of similar design and there is some overlap in their use and names. Subsoilers are heavy implements, equipped with rigid tines, and they are designed for primary tillage below ploughing depth to rectify deep compaction problems. Their use is generally followed by another primary tillage operation. Chisel ploughs are heavy implements designed for deep primary tillage and are generally equipped with rigid tines. Cultivators range from heavy to light implements and are used for shallow primary tillage or crop maintenance, and may be equipped with rigid or spring tines. The function and characteristics of chisel ploughs, as well as subsoilers and cultivators where these overlap, will first be described, followed by a description of their parts and operation.

A. Function and Characteristics

Chisel tines cut vertically through the soil forcing the soil to move up along the curve of the tine, which flexes and breaks the soil. The shattering effect, which becomes more pronounced near the surface, results in complete loosening of the soil. The effect of the chisel plough on the soil in comparison with other ploughs is shown in Figure ___ (@ Krause 1984, p 74, fig 17 + ). The chisel plough does not invert the soil, but does mix in surface residues. As shown in Table ___ (@ Godwin 1990, p 101, Table 4.1) there is approximately a 25% reduction in surface residues with each operation.

Chisel ploughs are most effective in soils that are dry or near dry. In moist soils the lifting and shattering action is not nearly so great. As discussed in Section 2.1.2.7 and shown in Figure ___ (@ McKyes 1985, p 34, fig. 2.21), when a tillage implement cuts the soil the strain set up in the soil ahead of the cutting tool results in mechanical failure along successive internal rupture surfaces, both ahead and to the side of the implement.

The lateral soil disturbance caused by two tines passing through dry soil is shown schematically in Figure ___ (@ Krause 1984, p 105, Fig. 34). The cross-section of the soil tilled by each chisel tine is roughly in the shape of a triangle, with the base of the triangle on the soil surface and its apex at the tip of the tine. This leaves the bottom of the tilled layer shaped like a washboard. The angle between the side of the triangle, perpendicular to the direction of travel, and the horizontal, varies with the moisture content of the soil. For relatively dry soils the angle is roughly 50 degrees, and as the soil moisture content increases this angle becomes wider and the tilled area smaller. The angle can increase to nearly 90 degrees in very moist soils, in which case only a narrow groove is cut and no loosening or shattering of the soil is accomplished. Furthermore, "sausages" of smeared soil are brought up to the surface that harden quickly and are difficult to crumble by later tillage operations. Narrow furrows may also be cut in soils that are not very moist when the operating speed is too low, i.e. less than 6
km/h, which is nearly twice the operating speed of draught animals. For chisel ploughing with animal draught power the soil should therefore generally be drier than for tractor draught power, and the distance between tines or furrows closer.

As the bottom of the tilled layer left by the chisel plough is shaped like a washboard it can be seen that the minimum tilled depth, between the furrows, is controlled primarily by the spacing of the tines. This aspect will be discussed further in the next section. The shape of the tines also affects the minimum tilled depth by affecting the size of the bottom furrows, for example, wide duckfeet chisels leave smaller subsurface ridges for the same tine spacing. The minimum tilled depth is an important criterion both for later operations, such as planting, and for the provision of a suitable growing medium for the plants.

When a chisel plough is used for primary tillage the operation frequently has to be repeated in order to achieve the required soil condition, especially when rear mounted tools are not used. When a repeat operation is required this should generally be done crosswise at greater depth than the first operation. However, on sloping land no operations should be done up or down the slope as this will increase the risk of erosion. The efficiency of chisel ploughs is considerably improved by the addition of rear-mounted tools for loosening, crumbling, levelling, mixing, packing, etc.

The chisel plough destroys weeds by cutting their roots and bringing the plants up to the surface where they can be desiccated. Overlapping duckfeet tines are often used for shallow tillage to cut the roots. The pointed tines used for deeper tillage do not overlap, but all the soil near the surface is loosened and the angle that the tines operate at brings the weeds up to the surface.

The chisel plough is used for the following purposes:
- Stubble tillage.
- Working in crop residues and manure.
- Mechanical weed control, and especially of root propagating weeds.
- Primary tillage.
- Loosening hard dry soil before ploughing.
- Breaking up compacted layers below the normal ploughing depth.

Chisel ploughs are suitable for primary tillage in arid and semi-arid areas because of their non-inverting action and because they loosen and mix the soil sufficiently without pulverising it. They also leave approximately 75% of the plant residue on the surface. As compared with mouldboard or disc ploughs this results in the following:
- Less water loss as moist soil is not transported upwards.
- A lower rate of decomposition of soil organic matter due to less aeration of the soil.
- Crop residues retained on the soil surface that reduce water evaporation and the potential for wind and water erosion.

The following advantages and disadvantages of the chisel plough are based on Krause et al (1984):

Advantages:
- Wide range of possible uses, see above.
- Suitable for use in the arid and semi-arid tropics, see above.
- They can often be used on extremely heavy soils where the quality and capacity of other types of ploughing are unsatisfactory.
- High rate of work compared to mouldboard and disc ploughs.
- The power requirement per tilled cross-section is less than that for mouldboard and disc ploughs.
- The 3-point lifting power required is comparatively low, and hence they can be combined with rear attachments to enable two or occasionally three operations to be accomplished in one pass.
They are effective against root-propagating weeds.
They are highly reliable and their servicing and adjustment requirements are minimal.

Disadvantages:
They require high speeds of 8 to 10 km/h when crop residues are to be worked in and so greater demands are made of the tractor and driver, especially when working across crop rows.
Primary tillage often needs to be repeated, and usually at increased depth and crosswise.
The working width and speed should exceed minimum values if a high work rate is to be achieved and so large tractors of at least 45 kW are required. This limits their use on small farms unless some form of multiple farm use is available.
The chisel plough can replace the mouldboard or disc plough to only a limited extent and so both implements are usually needed.
Their mixing action is often inadequate for working in straw on light soils.

B. Description and Operation

A chisel plough is shown in Figure ___(@ Krause 1984, p 109, fig. 38) and it consists of the headstock and frame, which is made up of a series of crossbars, to which are attached the tines and to these the chisels. A range of rigid or spring tines can be fitted onto a frame in staggered rows. These are described below:

Chisels:

The chisel is the main soil engaging component of the chisel plough and is subject to high continuous and impact loads and to high frictional wear. Good quality chisels are made of the same material as mouldboard plough shares, i.e. three-ply steel with outer layers of frictional wear resistant high carbon steel and a centre layer of impact absorbing low carbon steel. The two main variables involved in the selection of chisels are their lift angle and their shape.

The lift angle, or angle of attack, of the chisel is primarily determined by the angle of the tine, but it is also dependent on the shape of the chisel. The basic factors regarding the lift angle of the chisel are shown in Figure ___(@ Krause 1984, p 109, fig. 37) and described below:

- Vertical tine (A):
  This has the highest draught force requirement and it is difficult to keep it in the soil.
- Steep tine (B):
  This has a higher draught force requirement than C, but it shatters and crumbles the soil more effectively.
- Low lift angle tine (C):
  This has the lowest draught force requirement, but it only lifts the soil without adequately loosening it.

The minimum draught force requirement occurs at a lift angle of roughly 20 degrees. The appropriate lift angles for heavy chisel ploughs are around 30 degrees, and for cultivators are up to 60 degrees.

Tines:

The tine supports the chisel and attaches it to one of the crossbars of the frame. The tine is subjected to large impact and continuous forces. The material that they are made of is dependent on their type. There are four main types of tines used for chisel ploughs and cultivators and these are described below:

- Rigid tines:
  Used for deep tillage, particularly when made with a relatively low lift angle. They are straight or slightly curved and made of high-carbon steel. They are usually fitted with
shearbolts to prevent damage caused by hitting obstructions. Rigid tines are sometimes called shanks, or standards, especially on subsoilers.

- **Spring or cushion spring tines:**
  Generally used in North America where the chisel ploughs tend to be of lighter construction, and where they are often fitted with sweeps instead of chisels. They are mounted on hinges on the crossbar and cushioned by spiral springs.

- **Heavy-duty spring tines:**
  Used more in Europe and they tend to have two or three leaf springs bolted together to form heavy-duty tines. The vibrating action of the springs accentuates soil shattering.

- **Flexible or spring tines:**
  Used primarily on cultivators. They are flattened and slightly curved to allow diversion around obstacles, and are manufactured from a heat-treated steel-nickel alloy. Their strongly vibrating action accentuates soil shattering. They are not suitable for deep tillage.

**Frame and tine spacing:**

The chisel plough frame is made up of one to four parallel crossbars to which the tines are attached. It is made of flat, profiled or square tubes of steel.

As described previously the furrows dug by the chisels need to be closely spaced to achieve a relatively uniform tillage depth. However, if the tines are placed close to each other then blockages due to crop residues will occur. The tines therefore have to be staggered in rows behind each other to satisfy both these requirements. This is shown in Figure ____ (@Krause 1984, p 107, fig. 35). On some types of ploughs the tines are mounted by adjustable flanges onto the main frame, allowing adjustment of the tine and furrow distance.

The choices of chisel and tine types, tine distance and furrow distance and several other variables for subsoilers, chisel ploughs and cultivators are shown in Figure ____ (@Krause 1984, p 106, table 3). Note that the greater the working depth the greater the furrow distance used. This is because of the triangular shape of the cross-sectional area tilled by the chisel tine. On animal drawn chisel ploughs only one chisel is used so as to minimise the draught force requirement. The spacing of operations with animal drawn chisel ploughs need to be closer together than the furrow distance given in the table. This is because the speed of operation affects the amount of soil tilled by each tine as described earlier. Furthermore, it may also be necessary to carry the operation out under dryer soil conditions when animal draught power is used to improve soil shattering and the volume of soil tilled.

A simpler form of chisel plough is the single-bar, two row type. Its frame for the three-point linkage system consists of one heavy hollow bar with a headstock. Two alternating types of tines are attached to that bar, viz. straight tines pointing forwards and tines with the same angle of attack but with a wide loop at the top, curving backwards. Although this arrangement allows an acceptable distance between the tines in a row to be achieved, the distance between rows is about 40 cm whereas this distance should be at least 70 cm to ensure a free flow of soil and plant material. However, this shorter distance is acceptable for low levels of plant material and for some soil conditions.

**Linkage systems and depth and width adjustment for tractor draught power:**

Depending on their size, chisel ploughs are designed as trailer, semi-mounted or mounted implements. The working width of mounted implements is between 2 and 6.5 m. Lighter trailed implements can cover up to 12 m. The heavier implements have an articulated frame with wings, or outriggers, and supporting wheels that can be folded hydraulically for transport.
Adjustments for working depth:
- The plough frame should be completely level, both in the direction of travel and laterally, during ploughing to ensure that all the chisels work at the same depth.
- The working depth is usually controlled by the supporting wheels or by rear-mounted tools. The use of the depth control setting on the tractor's hydraulic system, when no supporting wheels are used, has not proved successful. The maximum depth is limited by the height of the frame.

Adjustments for working width:
- The plough's working width is determined by the number of tines and their spacing. A chisel plough should at least cover the entire width of the tractor, so that chisels work both of the tractor's wheel tracks to alleviate the compaction they cause. An extreme case of this are strip chisel ploughs, which leave a strip in the centre of the implement untouched and so require less draught power. The left-over strip has to be tilled on the return pass and this is difficult as the driver has to precisely follow the narrow strip which has to be tilled.

Check chains are used to prevent excessive lateral movement of the plough, especially during transportation. Without their use the tractor tyres and linkage system can be damaged. During operation with a correctly adjusted plough the check chains should be slack most of the time.

Linkage systems and depth adjustments for animal draught power:

The linkage system and depth control for animal drawn chisel ploughs is basically the same as that for animal drawn mouldboard ploughs as described in that section.

Power and Draught force requirements, sizes and work rates:

Tractor draught power:

In addition to the details given in Figure ____(@ Krause p 106, table 3), the following technical details are given:
- Working width: Up to 12 m.
- Working depth: Up to 40 cm.
- Weight: 120 to 450 kg/m.
- Overload protection devices: Shearbolts and spiral springs.
- Speed of operation: 6 to 10 km/h.
- Power requirements: 20 to 40 kW/m, or 5 to 10 kW/tine.
- Work rates: Speed (km/h) x width/10 (m) ha/h.

For the same powered tractor work rates can be achieved of roughly 30% to 50% higher than those with mouldboard or disc ploughs.

Animal draught power:

Although the draught force requirement for a chisel tine is lower than that required for a mouldboard plough for the same depth and soil conditions, in practical usage terms they are roughly the same. This is because, firstly; for a chisel plough to be effective the soil needs to be dryer than that required for mouldboard ploughing, so that the shattering effect of the chisel can be realised. Secondly; the chisel plough has to be operated at a deeper depth than the mouldboard or disc ploughs to achieve the same minimum tilled depth.

The work rates depend on the required furrow spacing. This in turn is dependent on the soil conditions, speed of operation and the tillage operation being performed. For example, animal drawn chisel ploughs are often used to only prepare the planting row, with the inter-row
area being left untilled or only shallow tilled with a harrow. Under these conditions work rates are very high.

5.3.1.4. **Subsoilers**

A range of subsoilers is shown in Figure ___(Photographs + @ FAO manuals). Subsoilers are heavy implements and they are designed for primary tillage below ploughing depth to rectify deep compaction problems. Subsoilers are similar to heavy chisel ploughs and their mode of operation and the effect that they have on the soil is the same. Most of the section on chisel ploughs therefore also applies to subsoilers and only their most notable features will be described in this section.

A. Function and Characteristics

The subsoiler is a heavy duty implement designed to operate below the normal depth of tillage and to loosen and shatter the soil. The passage of tractors and implements tends to create a hard layer or plough pan in some soils and to make them impervious to water. Shattering the compacted layer allows water to seep more easily into the soil profile and to assist root penetration.

The effect of subsoilers on the soil is the same as that of chisel tines. They cut vertically through the soil forcing the soil to move upwards, which flexes and breaks the soil. However, they are designed to operate at greater depths than chisel ploughs in order to break up deep compacted layers. Fracturing and some loosening of the compacted layer is sufficient to meet this requirement rather than thoroughly loosening the soil at depth. This requirement together with the requirement of minimising draught force is met by having the chisels at a low lift angle, as described in the section on chisel ploughs. Like chisel ploughs subsoilers are most effective in soils that are dry or near dry. In moist soils the lifting and shattering action is not nearly so great. If the soil is wet only a compacted path, which is of little value, is made through the soil.

Subsoiling is a costly tillage operation because of its high energy requirement. Tillage deeper than 250 mm is rarely profitable as a regular practice. The beneficial effects are usually temporary and frequently disappear after the first year. Subsoiling should only be carried out when there is a compaction problem to be rectified. Furthermore, as discussed in Section 2.1.2.7 parts B and D, it is important to identify the source of compaction and to alter the tillage and crop management practices to remove this source if possible.

B. Description and Operation

A very strong frame and tines are used due to the depth of operation and the high draught forces involved. The tines on subsoilers are commonly called shanks, or standards, because of their large size. Wings are sometimes attached behind the chisels to improve the lifting and loosening efficiency of these machines. The information given in the section on chisel ploughs relating to their description and operation generally also applies to subsoilers and will not be repeated here.

In addition to the details given in the section on chisel ploughs in Figure ____(@ Krause 1984, p 106, table 3), the following technical details are given:
- Working width: Up to 6 m.
- Working depth: Up to 60 cm, and occasionally 100 cm.
- Overload protection devices: Shearbolts.
- Speed of operation: -
- Power requirements: 40 to 60 kW/m, or 10 to 20 kW/shank.
- Work rates: Speed (km/h) x width/10 (m) ha/h
5.3.1.5. **Sweep Ploughs**

A range of tractor drawn and mounted sweep ploughs are shown in Figure ___(@ Krause 1984, p 250, fig. 122). They are heavy-structured implements equipped with V-sweeps designed primarily for dryland farming systems. They are used extensively in stubble mulch fallow systems to achieve maximum retention of surface residues, so as to maximise water infiltration and retention and to minimise soil loss due to erosion. Their action on the soil is essentially similar to that of the chisel plough equipped with wide duckfeet and only their most notable features will be described in this section.

A. **Function and Characteristics**

Stubble mulch tillage is based on subsurface tillage with sweeps or blades that undercut the surface, thus severing plant roots and retaining crop residues on the surface. Initial tillage is normally 10 to 15 cm deep with disc or subsurface tillage implements. The second and subsequent tillage operations are usually shallower than the first 7 to 10 cm, and are performed with the sweep plough, chisel plough, spring-tooth cultivator, or rodweeder. The tillage is performed as often as necessary to control weeds and to provide a soil mulch during the fallow period between crops. This protective layer reduces wind and water erosion, increases the infiltration capacity with heavy rainfall, reduces evaporation and pronounced rises in soil temperature, and controls surface crusting. These aspects were discussed in Section 2 and further details of the stubble mulch system are given by Unger (1984).

The effect of the sweeps or blades on the soil is similar to that of chisel tines. However, whereas the chisels cut vertically through the soil, sweeps cut primarily horizontally through the soil. They force the soil to move upwards over the sweeps, which flexes and breaks the soil, and then drops it back which further shatters the soil. The soil should be fairly dry for the operation to be effective, but because the sweeps are arranged to cover the whole width of operation the soil does not have to be as dry as that required for chisel ploughs.

The sweep plough is used for:

- Stubble tillage.
- Weed control during fallow.
- Primary soil tillage.

The major problem of the sweep plough is incomplete weed kill. For maximum weed control, tilling should be done on a hot day to promote desiccation of the weeds and when the soil is dry enough to crumble. Under most conditions, speeds above 8 km/h are necessary to get enough turbulence in the soil for good weed control. Improved weed control is obtained by adding attachments such as rotary hoes, rodweeders, etc. Surface residues are generally reduced by about 10% on each pass. Rolling coulters can be placed in front of each shank to cut cleanly through the residues and this provides a more uniform distribution of residues in the field.

B. **Description and Operation**

A strong frame is used with sweeps mounted on the end of standards in a staggered arrangement to allow for overlap. Due to the large size of the sweeps the standards are widely spaced and clogging by crop residues is not a problem. Implements of more than 3.6 m in width usually have flex points on the frame, where subunits of the implement are joined together, for uniform tillage on uneven land.

The geometry of the sweeps is shown in Figure ___(@ Krause 1984, p 249 and 251, fig 121 and 123). The cutting width of the sweeps range from 0.75 to around 2.0 m. The width of the individual blade, measured at right angles to its cutting edge, ranges from 15 to 20 cm.
The pitch or tilt angle ranges from 12 to 25 degrees. The angle of the blade measured relative to its cutting edge, or lift angle is around 35 degrees. The share point nose angle of V-blade ranges from 30 to 50 degrees, measured from one leading edge to the other. Wide-angled sweeps penetrate the soil better, but shedding of weed roots and residues is a problem that frequently requires a lower angle. Rigid tines with large tools are very vulnerable to obstacles in the soil.

The depth of operation usually ranges for 7 to 15 cm and is controlled by depth wheels.

Technical details:
- Working width: Up to 12 m.
- Working depth: 7 to 15 cm.
- Weight:
- Overload protection devices: Shearbolts, springs.
- Speed of operation: Approximately 8 km/h.
- Power requirements: Up to 25 kW per shank
- Work rates: Speed (km/h) x width/10 (m) ha/h.

5.3.1.6. Paraploughs

A paraplough is shown in Figure ___(@ Krause 1984, p 307, fig. 146). This implement is a type of shallow subsoiler designed to break up compaction zones while creating very little disturbance to the soil surface and to crop residues on the surface. Only their most notable features will be described in this section.

A. Function and Characteristics

The chisel point is attached to legs that are initially angled at 45 degrees and then bent vertically and attached to the frame. The legs pass through the soil shattered by the chisel point but are inclined such that they lift the soil and drop it back, causing the tilled layer to fracture and shatter with little disturbance to the surface residues. Since the soil is lifted as it flows over the legs, the loosening occurs along natural cracks resulting from the tension in the soil slice rather than from compressive forces as in the subsoiler. The action of the angled portion of the leg overlaps with the action of the leg in front of it, thus disturbing the subsurface soil and shattering the smear plane created by the tool in front. The implement operates efficiently at a depth of about 40 cm. and they leave a barely visible cut where the vertical portion of the leg passes through the soil.

Their action is fairly similar to that of sweep ploughs, but they are designed to operate at over twice the depth of sweep ploughs. Because of the action of the 45 degree legs on the soil they shatter and loosen the soil to a much greater extent than do subsoilers.

Paraploughs are ideal implements to use to rectify compaction problems in reduced or zero tillage systems, if it has been decided not to revert to a conventional tillage system for one season. They are also sometimes used in preference to subsoilers to rectify compaction problems in conventional tillage systems prior to ploughing, as they loosen the soil to a greater extent and they have much less of a tendency to bring large clods up to the surface in dry clay soils.

The soil loosening properties of the paraplough are primarily used in the following cases:
- Compacted headlands on fields whose structure is suitable in all other respects.
- Fields under reduced tillage or direct drilling which have been damaged by compaction. Used only when required and not usually on an annual basis.
- Fields whose soil types are marginally suitable for reduced cultivation systems. Usually
used on an annual basis.

- Soil under permanent grassland that needs to be loosened without seriously disturbing the sward.

Paraploughs have a high energy requirement because of the depth at which they are operated. Generally they should not be used on a regular basis, as outlined in the section on subsoilers.

B. Description and Operation

The individual tillage tools consist of 3, 4 or 5 legs when mounted or 6 or 8 when semi-mounted. The legs are attached to a heavy frame constructed much like that of a standard mouldboard plough. The legs are straight for the first 25 cm. where they are attached to the main frame, and are then angled at 45 degrees to the right. The angle is smaller for the high-clearance models that are designed to operate in heavy stubble. A long chisel with a low lift angle is attached at the end of the angled leg to minimise the draught force requirement.

A hinged flap, or shatter-plate, is located along the rear of the angled leg that can be adjusted to increase the lift of the soil to increase shattering. A disc coulter is set in front of the angled portion of the leg, at the same angle, to cut through crop residues. The operating depth is set by means of a rear wheel and by the depth setting on the 3-point linkage.

The following technical details are given:

- Number of legs: Mounted: 3, 4, 5. Semi-mounted: 6 or 8
- Working width: 0.5 m per leg.
- Working depth: Maximum of 35 cm.
- Weight: 830 to 3600 kg
- Overload protection devices: Shearbolts.
- Speed of operation:
- Power requirements: Approximately 18 to 26 kW per leg.
- Work rates: Speed (km/h) x width/10 (m) ha/h

5.3.1.7. Rotary Cultivators

A range of tractor mounted rotary cultivators are shown in Figure ___(Photographs + @ FAO manuals). Tractor mounted rotary cultivators are available in many sizes, suitable for use with tractors ranging from small single axle tractors to those over 150 kW. They consist primarily of a row of blades which rotate on a shaft transverse to the direction of travel and which is driven by the tractor's power take-off shaft (p.t.o.). They are used as either primary or secondary tillage implements. The function and characteristics of the rotary cultivator will first be described, followed by a description of its parts and operation.

A. Function and Characteristics

The rotating blades on the main shaft of a rotary cultivator may rotate in the same direction as the tractor wheels, or in the opposite direction. The former type of rotary cultivator is the more common and this mode of operation is known as concurrent revolution, and the latter as reverse revolution. These are shown in Figure ___(@ Krause 1984, p 123 fig. 50).

The blade is both rotating as well as moving forward and this results in a cyclical motion, as shown in Figure ____(@ Krause p 118, fig. 44). Concurrent revolving blades cut the soil when moving downwards and backwards. Reverse revolving blades cut the soil when moving forward and upwards. As shown in the above figure both types cut wedge-shaped slices. The length of each slice, measured along the soil surface in the direction of travel is called the bite length. These wedges of soil are also hit by the following blade and are thrown
against the hood that causes further crumbling. The hood also guides the flow of soil material and protects against flying stones, etc. One or more trailing screens extending over the entire working width may be used to level the soil surface.

The reverse revolution type has a screen of iron bars between the rotor and hood. This screen separates the course soil material, trash, etc., and deposits them before, and hence below, the fine material that passes through the bars. This results in satisfactory inversion and crumbling and for this reason this machine is frequently used for grassland renovation when a seedbed for sowing is made in one pass.

As the blade is both moving forward as well as rotating it is important that there is a clearance angle between the plane of the blade and the tangent to the cutting trajectory. This angle is shown in Figure ___(@ Krause, p 118, fig. 45). If this angle is too small the back of the rotor blade will be pushed into the uncut soil as the rotor moves forward, resulting in an increase in the power requirement and in the soil being smeared.

The rotary cultivator is used for the following purposes:

- Stubble tillage.
- Working in organic material.
- Mechanical weed control.
- Seedbed preparation.
- Sowing in one operation when combined with sowing equipment.
- Strip cultivation in row crops.
- Puddling in paddy rice production systems.
- Grassland and wasteland clearing.

As was shown in Figure ___(@ Krause p 74, fig 17 +) the rotary cultivator is very efficient at mixing the soil but it also pulverises the soil. Organic material can be well worked in if it is evenly distributed over the surface and this is an important use of the rotary cultivator. However, the pronounced pulverisation of the soil caused by a rotary cultivator, when the tillage intensity is high, destroys soil structure by substantially reducing soil aggregation. This combined with loosening of the soil also causes considerable decomposition of soil organic matter through aeration. Both of these actions are extremely damaging to the soil, especially under hot arid and semi-arid conditions, as discussed in Section 2. Extreme caution is therefore required when using the rotary cultivator in the tropics and subtropics.

Rotary cultivators should not be used on soils prone to soil erosion, unless they are being used to implement a tillage system which is designed to minimise soil and water loss, such as the stubble mulch tillage system. They can also be adapted to strip cultivation systems by removing some of the blade sets. These systems reduce soil organic matter decomposition and the risk of erosion to a limited extent, by leaving untilled strips of soil in between the tilled strips. There are far fewer objections to the use of the rotary cultivator in irrigated farming, especially in the case of surface irrigation. The rotary cultivator is also a very useful implement in paddy rice production systems.

Rotary cultivators are frequently combined with other implements allowing several operations to be undertaken in one pass. When combined with soil loosening tools such as chisels, mounted either in front of, or behind the rotor, and operating below the depth of the rotor, they make it possible to combine deep loosening with shallow crumbling and mixing. They are also frequently combined with packers to enable a seedbed to be produced in one pass.

The following advantages and disadvantages of the rotary cultivator are based on Krause et al (1984):

Advantages:
- In many cases only one pass is necessary to produce a seedbed, thus saving time and
operating costs, improving the timeliness of sowing, and reducing compaction due to frequent passes.

- The desired crumbling and mixing can be achieved under a wide range of soil conditions by varying the rotational speed of the rotor in relation to its forward speed.
- They are very suitable for working in organic matter, mulching, and also grassland clearing as they accelerate the decomposition of organic matter.
- Stubble tillage is still possible on hard firm soils where disc or rotary harrows cannot be used. This operation does, however, impose heavy demands on the rotary cultivator, tractor and driver and causes considerable wear.
- The production of tillage compaction soles is very low.
- The power transmission is very energy efficient, about 80%, as the main drive is off the p.t.o., and not through the wheels as in ploughing which has an efficiency of only about 50% due to slippage. They cause very little slippage of the tractor's wheels and so uphill working is possible.
- Their short length removes less load from the front axle of the tractor and this also enables them to be combined with other implements.
- They can be combined with mounted sowing machines to allow one pass tillage and sowing.

Disadvantages:

- The power required per volume of manipulated soil is high compared with a chisel plough because of the operating intensity.
- When the tillage intensity is too high, i.e. excessive rpm and low forward speed, the operation may result in damage to the soil structure and lead to crusting and soil erosion. A fairly high level of operator competence, and hence good training, is therefore required.
- The work rate is not always satisfactory, especially for deep tillage.
- A serious strain is imposed on the tractor p.t.o. and drive systems on hard stony soils.
- Compatibility is required between the tractor's p.t.o. and the implement, including; rotational speed; direction of rotation; shaft profile and location.
- The added complexity of p.t.o. driven implements places a greater demand on servicing, maintenance and spare parts availability.

Due to the above disadvantages great care should be taken when recommending the use of p.t.o. driven equipment in regions that may not have the appropriate infrastructure.

B. Description and Operation

The rotary cultivator is shown in Figure ____ (@Krause p 121, fig. 47) and it consists of the rotor with a number of working sets of blades, a chain drive, gearbox, safety clutch, p.t.o. driveshaft, hood, depth control wheels or skids, frame and 3-point headstock. The main components and their selection and adjustments are described below:

Rotor, and tillage intensity adjustment:

The rotor is mounted in the frame at right angles to the direction of travel and supported by bearings, either in the centre or at the ends. The soil engaging tools, known as blades or knives, are rigidly fixed on separate flanges in working sets. The blades are bent to the left and right in an equal number of pairs of 2, 4 or 6. The blades are arranged in a spiral pattern on the rotor so that only one blade hits the soil at a time, so providing a smooth operation. The rotational speed of the rotor is normally between 100 and 300 rpm.

A range of shapes of blades is available for various soil conditions and uses, and the main types are shown in Figure ____ (@Krause p 121, fig. 48). The rotor can also be fitted with tines or spikes for secondary tillage on ploughed land.

By varying the rotational speed of the rotor in relation to its forward speed different
levels of tillage intensity can be achieved. The tillage intensity can be measured in terms of the bite length of each blade. This is the length of each wedge cut off by each advancing blade, measured along the soil surface, as shown in Figure ___(@ Krause p 118, fig.44)

Adjustments for tillage intensity:
Figure ___(@ Krause 1984, p 124, fig.51) gives the required bite length as a function of design variables and speed adjustments. The design variables will depend on the range of tools available for the machine and the speed adjustments can be selected by the operator. The figure is used by starting with the required bite length and then drawing straight lines through axes 6, 4, and 2, selecting the appropriate design and speed variables and ensuring that the ends of the lines are joined. Manuals should be provided by the dealer to give the above information for correct tool selection and speed adjustment.

The following general points are made, based on Krause et al (1984):

- Low rotational speed and high forward speed results in clods being left and the soil structure being preserved.
- High rotational speed and a low forward speed of 1 to 1.5 km/h results in intensive tillage, and damage to the soil structure under hot dry conditions.
- The rotor's peripheral speed should be about three times the forward travel speed.
- The hood and trailing screen greatly influence the resulting tillth. Tillage intensity is increased as their positions are lowered.

Linkage and drive system and depth adjustment:

Larger rotary cultivators are usually mounted on the 3-point hitch system, categories 1 to 3 depending on size, and are only rarely available as a trailer unit. The tillage operation is performed with the hydraulic system in free-floating mode since the system is not required for depth control. The lifting capacity at the end of the tractor's lower links should be roughly twice the weight of the implement. The centre of gravity of the implement is located close to the tractor. Many rotary cultivators can operate in an offset position so that they can be adapted to the track width.

Adjustments for working depth:

- The depth is varied by adjusting the gauge wheels or skids by means of spindles or bolts.
- The usual depth is from 5 to 15 cm., but special machines can operate down to 30 cm depth. For seedbed preparation the tilling depth should not exceed 10 cm. Maximum depth is limited by the protective shield on the chain drive.
- Sickle-shaped blades work at greater depths than universal blades.
- Implements used in tandem with the rotary cultivator can also be used to control depth, and this applies particularly to rear mounted rollers.
- The lifting arms and top link of the 3-point linkage should be adjusted to ensure that the frame is level, both in the direction of travel and the lateral direction.

The speed of the rotor is normally between 100 and 300 rpm and this is geared down from the tractor's standard p.t.o. shaft drive speed of 540 or 1000 rpm. The higher rpm is now commonly used for the larger rotary cultivators to save the drive system and bearings. The gear wheels in the gearbox usually have to be changed when switching from 540 to 1000 rpm. It should be noted that a very high rotor speed requires a disproportionately high power from the p.t.o., and also imposes a high strain on the drive system.

The p.t.o. and driveshaft should have the same spline profile. When at working depth the telescoping joints of the shaft should overlap for at least 200 mm to allow a sufficient contact area for power transmission. At working depth the angle of universal joints in the driveshaft should not exceed 30 degrees. An overload safety device, such as a safety clutch,
strongly recommended, especially on hard stony ground.

When the rotor is driven from the centre, a narrow untilled ridge is left and a tine is sometimes used to break up this ridge. The drive is usually mounted on the side of the machine and its protective shield determines the maximum depth that can be tilled.

The following technical details are based on Krause et al (1984):

- Working width: Up to 4.5 m.
- Working depth: Normally 5 to 15 cm, with special machines down to 30 cm.
- Number of blades per set: 2, 4, or 6. Total up to 132.
- Distance between sets: From 20 cm up to 45 cm when used behind tines.
- Safety devices: Friction clutch, single or multiple disc.
- Weight: 350 to 500 kg/m.
- P.t.o. drive: 540/1000 rpm.
- Gearbox, rotor: Up to 10 steps.
- Rotor's peripheral speed: 4.0 to 7.5 m/s.
- Travel speed: Up to 6 km/h.
- Power requirements: Primary tillage at 3-4 km/h: 25-35 kW/m
  Secondary tillage: 18-22 kW/m
- Work rates: Speed (km/h) x width/10 (m) ha/h

5.3.2. Secondary Tillage Operations and Implements

The main objectives of tillage were given in detail in Section 5.3 and most of those objectives also apply to secondary tillage operations. Secondary tillage operations generally follow primary tillage. They are intended to create optimum germination conditions with regard to the soil structure, oxygen, water and nutrient supplies and the temperature. The depth of tillage is usually less than that of primary tillage and is done primarily to reduce the size of the clods produced by the primary tillage operation, to level and firm the soil, close air pockets, work in manure and chemicals, remove any surface weeds, and prepare a suitable seedbed. Stubble mulch tillage and fallow cultivation systems, which are particularly important in the arid and semi-arid regions, are also frequently implemented using tillage implements that are otherwise only used for secondary tillage operations.

Small seeds require a finer tilth in the seed zone than larger seeds to achieve good seed-soil contact. The size of the soil aggregates in the seed zone should generally be 1 to 5 mm in size with the smaller seeds requiring smaller aggregate sizes. This requirement determines the type and number of secondary tillage operations required to achieve this tilth. The general requirements of seedbeds were discussed in Section 2.4.1.1 with regard to planting requirements. It is important that this section is referred to again as the tilth and depth of tillage required is dependent on the soil type, seed size and climatic conditions.

The main secondary tillage implements are harrows, cultivators, hoes, levellers, rollers, and ridgers. A very wide range of implements is available and several of the former groups of implements are available with disc, tine or rotary soil engaging tools. The disc tiller and the rodweeder are specialised implements generally used only in dryland farming systems. As discussed in Section 5.3 the selection of the most appropriate implement for the job is dependent on a number of factors. Also as discussed in that section the depth of coverage given to secondary tillage implements will not be as great as that given to primary tillage implements. A wider and more detailed coverage of secondary tillage implements is given by Krause et al (1984).

The secondary tillage implements will be discussed within the following groupings:

- Disc type implements
  - Disc harrow
- Disc tiller

- Tined implements
  - Spike tooth harrow
  - Chain tooth harrow
  - Spring tine harrow
  - Tined cultivators

- Ground driven rotary implements
  - Rotary harrow
  - Rotary hoe

- P.t.o. driven implements
  - Rotary cultivator
  - Rotating hoe
  - Reciprocating hoe

- Compacting implements
  - Rollers

- Levelling implements
  - Levellers

- Ridging, bed shaping and pot-holing implements
  - Ridgers
  - Bed shapers
  - Tied-ridging units
  - Pot-holers

- Manual tillage implements
  - Hoes
  - Rakes
  - Wheeled weeders

5.3.2.1. **Disc Type Implements**

The disc type implements discussed in this section are the disc harrows and disc tillers. Some ridgers are also made using discs but these will be discussed in the section on ridgers.

A. **Disc Harrows**

A range of disc harrows are shown in Figure ____ (Photographs + @ FAO manuals). The characteristics and mode of function of disc type implements were covered in the section on disc ploughs. Disc harrows differ from disc ploughs in that they consist of two or more rows, or gangs, of discs. The discs operate at an angle to the direction of travel, which imparts a cutting and turning action to the soil. The discs on the different gangs turn the soil in the opposite direction, so that the side forces are cancelled out, and hence a tail wheel is not required as in disc ploughs. When these gangs are arranged one behind the other they turn the soil in opposite directions and the rear discs are also staggered by half the distance between the discs, thus a smooth finish is achieved with no "ridge and furrow" effect. This arrangement is particularly suitable for levelling operations.

Disc harrows are used for the following purposes:

- Stubble and fallow tillage.
- Working in long pliable plant material and manure.
- Keeping the soil surface open.
- Mechanical weed control.
- Levelling.
- Seedbed preparation, for intermediate crops and in ploughed fields with large clods.
- Working in broadcast seeds.
- Sod cutting before grassland is cleared.
Disc harrows are frequently used for fallow tillage systems. These involve increasing the infiltration of water by keeping the soil surface open; reducing soil water losses by reducing evapotranspiration, through weed control; and by reducing soil water evaporation from the lower layers, through the provision of a soil mulch.

Disc harrows are also commonly used for stubble tillage and often for stubble mulch tillage systems. However, disc harrows bury around 50% of the crop residues on each pass, see Table ___(@ Godwin 1990, p 101, table 4.1). Where the amount of crop residues are low disc harrows may not be suitable for stubble mulch tillage systems, as at least 30% of the surface area should be covered with residues for effective erosion control, see Section 2.2.1.3. The amount of residue buried in each pass depends on the design of the implement and operating conditions. Increasing the size, concavity and spacing of discs, the weight of the implement, and depth of tillage all increase the amount of residue buried in each pass. Disc harrows generally provide better weed control than sweep ploughs, which are also used in stubble mulch tillage systems. However, disc harrows are not very effective against root-propagating weeds. Their use can also result in excessive tillage intensity that can destroy the soil structure. The rolling action of the discs has been found to produce excessively fine soil fractions which increases the potential for erosion, Elwell (1983).

Cut-out or notched discs have a large cutting surface and are efficient at cutting into crop residues and penetrating into hard, dry soils. Plain discs are less efficient at cutting into crop residues but produce a better mixing action. For these reasons cut-out discs are frequently used on the front gangs with plain discs on the rear gangs. Scrapers should be fitted to remove soil sticking to the discs.

The gangs of discs can be attached to the frame in several different ways and these are shown in Figure ___(@ Krause p 136, fig. 55). For those arrangements where a centre strip is left untilled by the discs a chisel tine is commonly attached to till it. The disc gang angles can usually be altered so as to increase or decrease penetration and tillage intensity. Increasing the disc angle increases the cutting action and gives a greater working depth. Increasing the disc angle also increases crumbling and tillage intensity.

Disc harrows are generally unsuitable for animal traction. This is because of their heavy weight required for soil penetration, and their relatively high cost due to the complexity of mounting the rotating discs using bearings.

The following technical details are based on Krause et al (1984):

- Number of disc gangs: 2 to 12.
- Diameter of discs: 40 to 65 cm. Heavy duty max. 90 cm.
- Distance between discs: 16 to 30 cm.
- Weight per disc: 25 to 50 kg per disc.
- Disc angle: 14 to 23 degrees with direction of travel.
- Working width: 1 to 10 m.
- Working depth: 5 to 15 cm.
- Speed of operation: 5 to 8 km/h.
- Power requirements: 18 to 25 kW per metre width.
- Work rates: Speed (km/h) x width/10 (m) ha/h. Effective capacity at 5 km/h is 0.35 to 0.45 ha/h per metre of width.

B. Disc Tillers

A range of disc tillers is shown in Figure ___( Photograph + @ FAO manuals). The characteristics and mode of function of disc type implements were covered in the sections on disc ploughs. Disc tillers are intermediate in design between disc ploughs and disc harrows. The disc tiller is similar to the disc plough in that the discs all throw the soil to one side only. It is similar to the disc harrow in that a large number of discs are used, which may be mounted
on a gang or individually, and that the implement is used for shallow tillage. On larger implements the discs may be mounted in one or more gangs. To counteract the lateral forces produced by the discs an angled rear furrow wheel is required, and this is often complemented with a front wheel as well. Disc tillers are usually trailed and the wheels are set vertically when the implement is being transported.

The disc tiller only operates at shallow depths and similar to all disc implements the soil is raised by the discs and deposited in a pouring movement. The resultant mixing of the soil and the crop residues increases the infiltration rate, reduces evaporation and controls wind and water erosion. If the travel speed is too high, above 6.5 km/h, the tillage intensity becomes excessive and the tilth becomes too fine, and inversion also increases burying excessive amounts of crop residues, and hence increasing the potential for erosion.

The disc tiller adapts well to uneven surfaces, as the disc gangs are suspended in groups or the discs can be attached to the frame individually by means of loaded supports. The latter can be by means of springs, hydraulics or pneumatics. They can be fitted with rear mounted levellers or other tools to produce better levelling, crumbling and compaction. They can also be combined with sowing or fertilizing equipment.

The disc tiller is used mainly in dryland farming systems and especially for:
- Stubble and fallow tillage.
- Primary tillage.
- Seedbed preparation in one operation.
- Combined stubble tillage and planting in one operation.
- Working in broadcast seeds, manure, crop chemicals and plant residue.

The advantages of the disc tiller for dryland farming include the following; versatility; good mulching action; possibility of combining it with other implements and especially sowing equipment; high field capacity; good adaption to uneven surfaces; and a relatively low energy requirement. Its main disadvantage is its high cost.

The working width and disc angle are adjusted from one central point by a hitch brace rod so that every disc has the same setting. The disc angle can be set between 30 and 60 degrees, usually 40 to 50 degrees, and the working width between 70 and 100% of the maximum width. The depth is adjusted by cranks on the furrow and depth wheels or by a hydraulic system remotely controlled from the tractor. The hitch point can also be adjusted to distribute the load more evenly over the implement.

Penetration is improved by increasing the disc angle. Tillage intensity is increased by increasing the disc angle, the concavity of the disc and the speed of operation.

The following technical details are based on Krause et al (1984):
- Number of disc: 10 to 40.
- Diameter of discs: 45 to 60 cm.
- Distance between discs: 15 to 26 cm.
- Weight per disc: 120 to 135 kg per disc.
- Disc angle: 30 to 35 degrees with direction of travel.
- Tilt angle (fixed): 0 or 15 degrees.
- Working width: 1 to 4 m
- Working depth: 5 to 15 cm.
- Speed of operation: 5 to 8 km/h.
- Power requirements: 28 to 45 kW per metre width.
- Work rates: Speed (km/h) x width/10 (m) ha/h.
  Effective capacity at 6.5 km/h is 0.6 ha/h per metre of width.
5.3.2.2. **Tined Implements**

Tined implements consist of rigid or flexible tines attached to a frame. The implements discussed in this section are the spike tooth, spike chain and spring tine harrows, and the tined cultivators.

A. **Spike Tooth and Spike Chain Harrows**

A range of spike tooth and spike chain harrows is shown in Figure ___(@ Krause 1984, p 196, fig. 96). These implements are used for light tillage operations, with the depth of cultivation seldom being greater than 5 cm.

Spike tooth and spike chain harrows have rigid spike soil engaging tools. These spikes impact against soil clods and break them into smaller pieces. These pieces are thrown sideways and are smashed again by the following spikes that are attached in a staggered arrangement. This process is furthered by the slight swinging motion of the harrow which smooths and levels surface irregularities. Because of the flexibility of the spike chain harrows they can also be used to cultivate ridge and furrow systems without demolishing the ridges.

Spike tooth and spike chain harrows are used for the following purposes:

- Crumbling and aerating the soil.
- Loosening and roughening the surface of crusted soils.
- Working in and mixing organic material, fertilizers and chemicals.
- Levelling.
- Mechanical weed control.
- Shallow seedbed preparation.
- Working in broadcast seeds.

The main advantages of these harrows are their simple and inexpensive design and that they are suitable for use on most types of soil. Because of these factors, together with their low power requirements, they are also suitable for use with animal traction. The spike tooth harrow in particular is one of the most common animal drawn tillage implements after the plough. Furthermore, these implements can easily be made by rural blacksmiths. Harrows are excellent tools for filling the air pockets in tilled soil and for producing a soil mulch to reduce water evaporation. Their disadvantages include jumping in hard dry soils, which results in an inadequate crumbling action, destruction of the soil structure with over-intensive tillage and their tendency to clog up when used in fields with heavy weed populations or heavy crop residues.

The links of the spiked chain harrow form a mesh without a frame. Each link is made of bent steel wire in various shapes and an example is given in Figure ___(@ Krause p 198, fig. 98). Two tines are fitted to each link perpendicular to the surface of the mesh. Short tines are placed on one side and longer ones on the other so that the mesh can be inverted to change the depth of operation. The depth of operation is also changed by speed and the height of the hitch point.

Spike tooth harrows are equipped with rigid or articulated frames to which the teeth are attached. The teeth are arranged in sections approximately 1 m wide and chains attach these sections to a supporting frame or hitch bar. The teeth are available in straight, angled or shovel shapes, and have a square upper section which fits into a square opening in the bar so that it does not turn. The front row of teeth are generally straight and the following ones curved towards the direction of travel. The working depth can be increased by adding extra weights to the frame. The teeth also affect the depth control, with angled and curved teeth penetrating more deeply into the soil than straight teeth when pointing forwards, but not so deeply when pointing backwards.
The tillage intensity is altered as follows:

- **Low speeds of less than 4 km/h:** Coarse tillage, with loosening and aeration of the soil but hardly any crumbling or mixing.
- **High speeds of 4 to 12 km/h:** Intensive tillage with pronounced crumbling and mixing.
- **Minimum number of widely spaced teeth:** Coarse soil surface and less weed control.
- **Maximum number of teeth:** Fine crumbling and mixing and maximum weed control.
- **Close mounting of the harrow sections on the supporting frame:** Minimum swinging action, coarse tillage which is uniform over the entire working width.
- **Loose mounting of the sections:** Lateral swinging of the harrow, intensive tillage but with untilled patches.
- **Sharp teeth will crumble the soil more satisfactorily than blunt ones.**

The following technical details for tractor drawn harrows are based on Krause et al (1984):

<table>
<thead>
<tr>
<th></th>
<th>Spike tooth</th>
<th>Spike chain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Working width:</strong></td>
<td>Up to 14 m.</td>
<td>Up to 4 m.</td>
</tr>
<tr>
<td><strong>Working depth:</strong></td>
<td>Up to 8 cm.</td>
<td>Up to 5 cm.</td>
</tr>
<tr>
<td><strong>Speed of operation:</strong></td>
<td>Up to 12 km/h.</td>
<td></td>
</tr>
<tr>
<td><strong>Power requirements:</strong></td>
<td>Approx. 3 kW per metre width at 8 km/h.</td>
<td></td>
</tr>
<tr>
<td><strong>Work rates:</strong></td>
<td>Speed (km/h) x width/10 (m) ha/h.</td>
<td></td>
</tr>
</tbody>
</table>

B. Tined Cultivators and Spring Tine Harrows

A range of tined cultivators and spring tine harrows are shown in Figure 3(PHoto DAGFAO Ch 3). These implements are similar in appearance and operating characteristics to chisel ploughs, but are of a much lighter construction. Their mode of function and main characteristics were described in the section on chisel ploughs. Tined cultivators are a general purpose tool and may be used for operations ranging from light primary tillage to seedbed preparation.

Spring tine harrows are a lighter and simpler version of tined cultivators. Because of their lightness, the purposes for which they are used are generally more similar to that of spike tooth harrows than tined cultivators.

Tined cultivators are used for the following purposes:

- Stubble and fallow tillage, but only short stubble without straw.
- Working in manure.
- Levelling.
- Weed control, also in row crops.
- Seedbed preparation, especially shallow and medium deep.
- Grassland maintenance and clearing.

An important advantage of tined cultivators is that due to their relatively light weight they can be combined with rear mounted rollers to accelerate seedbed preparation. Some of the heavier cultivators are also available with seed boxes for precision planting. Tined cultivators do not generally operate well in dry hard soils with a large proportion of stones and roots. They are also generally unsuitable for use in stubble mulch systems, or for use on lands with high weed populations, as they are liable to choke.

A very large number of different types and sizes have been developed for specific climatic and soil conditions. The main types are described below:

- **Spring loaded rigid tine cultivator:**
  
The spring loading is designed primarily as a safety feature and produces little vibratory action on the soil. This cultivator is used for light primary tillage as well
as secondary tillage on all types of soils. The furrow distance is approximately 10 cm and so they are only suitable for deeper tillage. To ensure complete coverage the working depth should be at least equal to the furrow distance. They can be used for some stubble mulch systems provided the crop residues are short and light so that they do not choke the implement. Choking is reduced by increasing the spacing between the tines while retaining the same furrow distance, see section on chisel ploughs. They have a pronounced levelling action, even on fields with large clods or with wheel tracks. Pointed chisels are mainly used but a range of shapes are available for different operations, see Figure ____(@ Krause p 165, fig. 72). Available with 5, 7, 9, 13 and 15 tines, covering tractors from 20 to 55 kW. A seed box is usually available for this type of cultivator.

- **Coil shank cultivator:**
  Similar to above but the tine has a slightly greater vibratory effect on the soil. If equipped with an extra spring, the tine can produce a uniform working depth even on heavy soils and at high speeds. A seed box is not available.

- **Spring tine cultivator:**
  The spring steel tines are designed to pulverise the soil by their vibratory action, and so produce intensive crumbling of the soil. The furrows are spaced roughly 5 cm apart and so shallow tillage is possible. The tines are widely spaced on several crossbars to reduce the risk of choking. These cultivators are used for secondary tillage only. Rooted weeds are pulled upwards towards the surface and the soil is shaken off by the vibration so that the weeds dry rapidly. Available as mounted or trailed versions. Outriggers can be folded mechanically, with the use of springs, or hydraulically on very wide implements.

- **Inter-row cultivator:**
  Used for post emergence tillage operations. Available with a wide range of tines, sweeps, ridgers and other specialised attachments.

- **Animal drawn inter-row cultivator:**
  Rigid tined cultivators are available for use with animal draught power. (Due to the low speed of draught animals the vibratory effect of spring tine cultivators is minimal and hence they are generally not used). Most versions have a facility for adjusting their width so that they can be used for inter-row crop cultivation. In this arrangement rigid tines cultivators constitute an important tillage tool for animal draught power systems.

Tractor drawn cultivators are mainly used in combination with harrows, packers or levellers to form seedbed combinations. The easing of the load on the tractor's front axle due to the weight of these combinations must be taken into account. When used alone cultivators are very simple to operate, but seedbed combinations require accurate adjustment.

The tillage intensity of cultivators can be increased only by increasing the travel speed. Speeds up to 10 km/h are possible. With regard to other adjustments it is essential to maintain a uniform shallow working depth during full width preparation of a seedbed. The depth of operation of cultivators is controlled by gauge wheels on the supporting frame, and by adjusting the upper link of the 3-point linkage system to ensure level operation at working depth. When used in combination with rear mounted rollers the depth of operation of the cultivator, and the roller, is altered by reducing or increasing the load that the cultivator imposes on the roller. This is achieved by raising or lowering the point of attachment of the roller to the cultivator.

The following technical details for tractor drawn cultivators are based on Krause et al (1984):

- **Working width:** Up to 18 m.
- **Working depth:** 5 to 15 cm.
- **Weight:** 100 to 300 kg/m for single implements up to seedbed combinations with...
double roller harrow.
- Speed of operation: Up to 10 km/h.
- Power requirements: Approx. 0.75 kW per tine.
- Up to 18 kW/m for seedbed combinations at high speeds.
- Work rates: Speed (km/h) x width/10 (m) ha/h.

5.3.2.3. **Ground Driven Rotary Implements**

Ground driven rotary tillage implements consist of tines attached in a wheel like arrangement that rotates around a shaft, and where the power required for their tilling action is provided by the draught power of the tractor pulling them through the soil. The two types of implements discussed in this section are the rotary harrows and the rotary hoes.

**A. Rotary Harrows**

A range of rotary harrows is shown in Figure ___(@ Krause 1984, p 140, fig. 59). The soil engaging tools consist of sets of two blades mounted perpendicularly to each other and mounted on a rotating gang, similar to that of the disc harrow. As the implement is pulled forward the blades inserted in the soil are held by it and the implement's forward motion causes the gang to rotate, so that the other knives on the gang cut into the soil. As the gang is angled to the direction of travel the blades tear the soil as they are rotated out of it. The soil is transported sideways, but in opposite directions, by the front and rear gangs, and is crumbled and mixed in the process. Surface residues are reduced by 15 to 30% on each pass depending on the design and operating conditions of the implement.

The rotary harrow can be used on light, heavy and stony soils for the following purposes:
- Stubble and fallow tillage.
- Working in chopped short material and manure.
- Weed control.
- Seedbed preparation.
- Breaking up crusts and aerating the soil.
- Cutting grass sods.

The rotary harrow is often combined with a crumbling roller, especially for seedbed preparation. It is also used as a rear mounted attachment for the chisel plough.

The main advantages of the rotary harrow include the following; good mulching action on light to medium heavy soils; no smearing due to its tearing effect on the soil; it leaves a coarse surface; versatility; simplicity; and low cost. Its disadvantages include its inability to work in long plant material satisfactorily; its risk of wrapping of plant residues around the shaft; the high working speed required; that two or more passes are required to complete an operation; and that it is not particularly effective on hard soils.

The rotary harrow is usually mounted with the 3-point hitch system. Wide harrows of more than 3 m can be folded hydraulically, while extended harrows can be carried lengthwise on a trailer. The upper link is often a chain or the entire harrow may be suspended from one heavy chain. They follow the contours of the soil and usually do not have to be lifted for turns because of the flexible mounting of the hitch and blade gangs that can move vertically.

Commonly two to six gangs are mounted on a steel frame with adjustable slide bearings. The blades on gangs mounted next to each other and behind each other throw the soil in opposite directions, so as to counteract side forces and to leave a level surface respectively. Two sets of blades, curved to one side and roughly 40 cm long, are mounted perpendicularly to each other at their centres to the gang, see Figure _____(@ Krause p 144, figure 61). Successive sets are staggered at 45 degrees in a spiral pattern. Straw rejecters on
the shaft bearings reduce wrapping.

The angle between the gangs and the direction of travel, defined as the blade angle or grip, is adjusted by shifting the mountings on the frame. The blade grip adjustments are given in Table ___(@ Krause p 143, table 7). The more the gangs are angled away from 90 degrees the greater the tillage intensity, i.e. the greater the mixing and crumbling action. The intensity of the tillage is also strongly influenced by speed, which should be between 8 and 15 km/h. The working depth can be increased by adding extra weights to the implement.

The following technical details for rotary harrows are based on Krause et al (1984):
- Number of gangs: 2 to 8.
- Working width: 1.5 to 5 m.
- Working depth: Up to 12 cm.
- Weight per metre of working width: 150 to 250 kg/m.
- Speed of operation: 8 to 15 km/h.
- Power requirements: 15 to 25 kW/m.
- Work rates: Speed (km/h) x width/10 (m) ha/h. Effective capacity at 12 km/h is 1 ha/h per metre of working width.

B. Rotary Hoes

A range of rotary hoes is shown in Figure ___(@ Krause p 145). These implements are also known as mulch treads, skew treads, and rotary or rolling cultivators. The soil engaging tools of these implements consist of working sets of 10 to 18 radial, slightly curved tines, of a diameter of about 500 mm. These working sets are known as spider wheels and they are mounted on gangs perpendicular to the direction of travel.

Generally, the curved tines point forward when in operation. In this mode the tines' sharp tip contacts the soil vertically and penetrates to a depth of 25 to 50 mm, depending on the weight and condition of the soil. The tools are rotated by the soil's resistance and the emerging tines throw the soil upwards. This action breaks soil crusts and the roots of weeds are destroyed or brought up to the surface where they can be desiccated. The gangs are generally angled to the direction of travel producing an action similar to that of rotary harrows, i.e., the blades tear the soil as they are rotated out of it transporting the soil sideways. The best results are obtained either before the emergence of the crop or when the plants are tall enough to withstand the treatment without serious damage.

When shallow tillage is required the implement can be drawn backwards so that the tines do not penetrate deeply into the soil. In this mode of operation the implement can be used to compact a seedbed, work in broadcast seeds, tread a layer of surface material into the soil, or spread plant residue evenly over the surface without choking. When the rotary hoe is used in row crops the crop can be protected by special screens or discs. The hoe is also used as a rear mounted tool behind chisel or sweep ploughs.

The rotary hoe is used for the following purposes:
- Weed control in row crops.
- Ridging for plant rows and forming ridges before planting.
- Soil preparation in irrigation practices.
- Crumbling and packing of seedbeds.
- Working in broadcast seeds, manure, fertilizers and chemicals.
- Breaking up crusts, loosening and aeration. Can also be done over germinating seeds.
- Flattening stubble and other crop residues so that they can be worked in more satisfactorily.

The main advantages of the rotary hoe include the following; an ideal implement to use
for weeding of row crops; a high field capacity due to a high speed of operation of 8 to 14 km/h; it can be used on soils with a wide range of moisture contents; a low draught power requirement; good manoeuvrability; easy to use and maintain; and it can be combined with other implements. Its main disadvantages are that it may form a compacted layer at a shallow depth, and that it is not particularly effective with larger weeds and there is a serious risk of choking.

There are two main types of rotary hoes. In the first type the spider wheels are usually fabricated and roughly 12 of them are mounted on two parallel gangs, one in front of the other, in a sub-frame. These sub-frames are mounted flexibly on the main frame so that the tools can follow uneven surfaces. In the second type the spider wheels are usually made of cast iron and 3 to 7 of these are mounted in a single gang in a light frame. These light frames are mounted on round shanks to a tool bar such that their position and inclination can be changed as shown in Figure ___(@ Krause p 146, fig. 62). This flexibility allows them to be used in row crops and to weed or form ridges and furrows. The mounting of the shank to the toolbar is often hinged to allow the individual gangs to follow uneven surfaces.

The rotary hoe is either mounted to the 3-point hitch system and used in the free-floating mode or simply employed as a trailer implement. Very wide implements can be folded for transport.

The depth of operation is determined by the weight of the implement and it can be increased by adding extra weights. On some types the gangs are spring loaded. The depth of operation can be reduced by drawing the implement backwards. The sub-frames can be adjusted to allow inter-row cultivation. They can also be angled to the direction of travel, which throws the soil to one side. When this setting is combined with inclining the implement to the horizontal they can be used to till ridges or to build them up. They can also be used to demolish or move ridges. Tillage intensity is increased by increasing the angle of the spiders to the direction of travel, also known as the "grip", and by increasing the speed of operation. The best work is achieved between speeds of 8 and 14 km/h.

The following technical details for rotary hoes are based on Krause et al (1984):

- Working width: 1 to 8 m.
- Working depth: 2.5 to 5 cm.
- Weight per metre of working width: 150 to 200 kg/m.
- Speed of operation: 8 to 14 km/h.
- Power requirements: 5 to 10 kW/m.
- Work rates: Speed (km/h) x width/10 (m) ha/h.

5.3.2.4. P.T.O. Driven Implements

In p.t.o. driven tillage implements the power required to drive the implements is supplied wholly or partially by the tractor's p.t.o. The main advantages and disadvantages of p.t.o. driven tillage implements listed below are based on Krause et al (1984):

Advantages:

- The tillage intensity of these implements, especially their crumbling and mixing actions, can be adapted more easily than passive implements to the soil type and prevailing moisture conditions. Consequently a field can be prepared for sowing in a single pass, and this applies even to heavy soils.
- They use the tractor's power more efficiently, roughly 80% efficiency compared to 50% for trailed passive implements, due to reduced wheel slip.
- The short length of the implements, plus their ability to prepare a seedbed in one pass, makes it possible to prepare a seedbed and to plant in one pass, thus substantially reducing energy input and soil compaction.

Disadvantages:
Compatibility is required between the tractor's p.t.o. and the implement, including; rotational speed; direction of rotation; shaft profile and location.

A fairly high level of operator competence is required, and hence good training, to ensure that forward speed is compatible with rotational speed so as to achieve the desired results for the prevailing conditions. Severe damage to soil structure can result from incorrect adjustments.

The added complexity of p.t.o. driven implements places a greater demand on servicing, maintenance and spare parts availability.

Due to the above disadvantages great care should be taken when recommending the use of p.t.o. driven equipment in regions that may not have the appropriate infrastructure.

The soil engaging implements may be driven in several different ways, and the following will be briefly described in this section:

- **Rotary cultivators:** Rotated vertically around a horizontal shaft perpendicular to the direction of travel.
- **Rotating hoes:** Rotated horizontally.
- **Reciprocating hoes:** Reciprocated transversely to the direction of travel.
- **Rodweeders:** A horizontally rotating shaft below the soil surface.

It should be noted that whereas the first three implements are designed to crumble and mix the soil, the fourth is primarily designed for weeding in dryland farming systems. It should also be noted that rodweeders are also commonly ground driven and that some models of ground driven rotary cultivators also exist.

A more detailed coverage of these implements is given by Krause et al (1984).

### A. Rotary Cultivators

Rotary cultivators have already been described in the section on primary tillage. When used for secondary tillage they may be fitted with tine rotors rather than blade rotors, and inter-row rotary cultivators are used exclusively for secondary tillage, see Figure ____ (Krause 1984, p 170, fig. 77).

The large number of tines on a tine rotor produce a better crumbling action than does a blade rotor, and a tillage pan cannot be formed. However, the levelling and mulching action is much less satisfactory than with the blade rotor. The inter-row rotary cultivators are normally used in very hard weed infested soil conditions. They are also available with rear mounted ridging units to remake a ridge after a pass with a cultivator.

On forward rotating rotary cultivators, concurrent, all the power required to drive the implement is provided by the tractor’s p.t.o. and it does not have a draught power requirement.

### B. Rotating Hoes

A range of rotating hoes is shown in Figure ____ (@ Krause p 177 fig. 83 and fig. 84). These implements consist of a series of sets of vertical tines that are rotated horizontally. Each set of two to four vertical tines are mounted on a carrier which is rotated by a horizontally mounted gear, which in turn drives the next gear and carrier and set of tines. As these rotating tines are pulled through the soil they move in a horizontal cyclical path.

The main use of the rotating hoe is for seedbed preparation. They are particularly suitable for secondary tillage of chisel ploughed fields, even with large amounts of stubble. The rotary hoe is generally not suitable for primary stubble tillage especially when long straw has to be worked in. By removing tines from a carrier the implement can be used in row crops.

Rotary hoes have a good crumbling action and they also produce good levelling. The
vertical mixing action is weak, which is advantageous when it is not desired to bring moist soil from lower levels up to the surface, which would increase moisture loss. Their disadvantages include their vulnerability to damage by stones and their unsatisfactory performance in moist soils.

Tillage intensity is dependent on the ratio between the tools' forward speed and the circumferential speed of the tines. Crumbling is increased by increasing circumferential speed and reducing forward speed. A general rule for satisfactory operation is that the circumferential speed of the tines should be twice the forward speed, with the latter not exceeding 6 km/h. The rpm of the rotor sets can be varied from approximately 130 to 480 by changing the gears. Tillage intensity is also increased by increasing the number of tines on each carrier from two to four. Depth is usually controlled by the mounting of a rear mounted cage roller.

Roughly one third of the power required by the implement is in the form of draught power and roughly two thirds in the form of p.t.o. power. The rotating hoes’ gearbox can be equipped with a rear extension shaft so that other p.t.o. driven implements can be attached behind it.

The following technical details for rotating hoes are based on Krause et al (1984):

- Working width: 1 to 9 m.
- Working depth: Up to 25 cm.
- Travel speed: 5 to 7 km/h.
- RPM of the p.t.o.: 540 or 1000.
- Circumferential speed of the rotor sets: 1.8 to 6.5 m/s.
- Weight per metre of working width: 170 to 330 kg/m.
- Power requirements: 15 to 30 kW/m.
- Work rates: Speed (km/h) x width/10 (m) ha/h.

C. Reciprocating Hoes

A range of reciprocating hoes is shown in Figure ...(@ Krause p 179 fig. 85). These implements consist of two to four bars mounted horizontally on a frame in parallel to each other and perpendicular to the direction of travel. A number of tines are attached to each bar. The bars are driven in a reciprocating motion by a heavy crank wheel driven by the tractor's p.t.o. The bars are driven in opposite directions to cancel out side forces and vibrations, and their frequency is between 140 and 540 oscillations per minute. As these reciprocating tines are pulled through the soil they move in a horizontal sinusoidal path.

The main use of the reciprocating hoe is for seedbed preparation. They can also be used for secondary tillage of chisel ploughed fields, provided only small amounts of stubble remain on the surface otherwise clogging may occur.

Reciprocating hoes have a good crumbling action and they also produce good levelling. Similar to the rotating hoes the vertical mixing action is week, which is advantageous when it is not desired to bring moist soil from lower levels up to the surface.

Tillage intensity is controlled only by the forward speed as the frequency of oscillation of the tines, their stroke and number per bar are fixed by the manufacturer. The tillage intensity decreases as the speed increases and at excessive speeds soil is pushed up in front of the machine. Generally the speed should not exceed 6 km/h for satisfactory results. Depth is usually controlled by the mounting of a rear mounted cage roller.

Roughly two thirds of the power required by the implement is in the form of draught power and roughly one third in the form of p.t.o. power. The draught requirement increases with forward speed while the rotational requirement remains relatively constant.
The following technical details for reciprocating hoes are based on Krause et al (1984):

- Working width: 2 to 6 m.
- Working depth: Up to 20 cm.
- Travel speed: 5 to 7 km/h.
- RPM of the p.t.o.: 540.
- Frequency of bars: 140 to 540/min.
- Weight, including roller: 300 to 300 kg/m of width.
- Power requirements: 15 to 22 kW/m.
- Work rates: Speed (km/h) x width/10 (m) ha/h.

D. Rodweeders

A range of rodweeders is shown in Figure ___ (@ Godwin 1990, p 98 fig. 4.13). This implement is equipped with a square rod of roughly 25 mm that rotates backwards to the direction of travel and parallel to the surface. Rodweeders are driven by the p.t.o., a ground wheel or hydraulic motor operated from the tractor. A variation of rotary rodweeders are dead rods which do not rotate. Rodweeders are frequently mounted behind sweep ploughs or chisel tines.

The rodweeder has been developed specifically for dryland farming systems. The square rod rotates slowly against the direction of travel at a depth of approximately 5 to 10 cm. As the soil is forced to pass over the rod it is lifted and loosened. This increases infiltration capacity. It also disrupts the capillary continuity between the surface and lower layers creating a soil mulch. The rotating action of the rod also firms the soil under the rod, which combined with the soil mulch, further reduces evaporative losses from the lower layers. The slight firming is also desirable for seedbed preparation. The reverse rotation of the square rod pulls up roots of weeds and leaves them on the surface to dry out, thus saving moisture loss from evapotranspiration. Only 10% of crop residues are worked into the soil, leaving a plant mulch to protect against erosion, evaporation and excessive heating. Coarse soil material is also moved upwards and deposited over the fine material thus further protecting the soil against erosion. Rodweeders are frequently combined with sweep ploughs or chisel ploughs so that the latter can provide deep loosening and soil shattering.

Rodweeders are used primarily for the following operations:

- Stubble tillage.
- Weed control during the summer fallow period.
- Secondary tillage before sowing.

Penetration is a problem on hard and dry soils. This problem can be overcome to some extent by combining the implement with sweep or chisel ploughs. The implement is unsuitable for soils containing stumps, roots or stones.

Dead rods are used directly behind sweeps or chisels to improve weed control. They generally require more draught energy than rotary rods, and do not firm the soil or clear weed roots as effectively.

The rotary rod is mounted in covered bearings between widely spaced angled or curved tines. Although only shallow tillage is performed a high frame is used to prevent choking when working with large amounts of crop residues. Spring, shearbolts or hydraulic overload protection devices are commonly used. Depth is usually controlled by means of depth wheels. These are also used to drive the rod in ground driven models. Very wide units up to 25 m are available and these have articulated frames. Each unit is about 3 m in length and driven by its own wheels. The operational speed is roughly 8 km/h and the rotational speed of the rod must correspond to the forward speed.

The following technical details for rodweeders are based on Krause et al (1984):
- Working width: Up to 25 m.
- Working depth: Up to 12 cm.
- Distance between tines: Up to 2 m.
- Travel speed: 8 km/h.
- RPM of the p.t.o.: 540 or 1000.
- RPM of rodweeder: at 8 km/h.
- Power requirements: 5 to 10 kW/m.
- Work rates: Speed (km/h) x width/10 (m) ha/h.

5.3.2.5. **Compacting Implements**

Primary tillage operations often cause excessive loosening of the soil. Consolidation occurs naturally over time but in many regions or for some cropping systems this process needs to be speeded up. In arid regions excessive deep loosening can cause excessive aeration and result in serious moisture and soil organic matter loss during dry periods. This can be reduced by compacting the soil surface immediately after primary tillage to reduce gaseous exchange between the surface and lower layers and hence reduce evaporation and moisture loss.

In moist soils compaction can be used to speed up the drying of soils. Compacting the soil reduces the pore volume, and hence the amount of water that can be held, and also increases capillary continuity between water particles and thus increases evaporation. Seedbeds are also frequently compacted to ensure good seed soil contact so as to improve germination. It is particularly important that the soil under the seed is in capillary continuity with deeper soil water, and it may be necessary to compact the soil to achieve this in excessively loosened soil.

The rollers are the only implements whose primary function is to compact the soil. However, the rotary hoe, when operated backwards is also used to lightly compact the soil for seedbeds and ridges. The leveller can also be used to compacts the soil as a secondary function when additional weights are added to it.

### A. Rollers

A range of rollers are shown in Figure ____(@ Krause p 190, figs. 91, 92, 93, 94). These include smooth rollers, corrugated rollers, subsurface packers, and crust breakers.

The roller compacts the soil by exerting pressure on the soil surface. This pressure is dependent primarily on the weight of the roller and the surface area of the soil it is in contact with. The latter depends on the roller's diameter and shape, and the way in which it is free to adapt to any unevenness of the soils' surface. Another important factor is that the amount of compaction is also dependent on the length of time that the force is exerted and this is dependent on the speed of operation. The pressure also causes the pulverisation of the clods on the surface. The roller's shape also has an important influence on the depth to which crumbling and compaction occur.

Care needs to be exercised when using the roller in regions where there is an erosion potential, as the roller levels and compacts the soil surface which reduces the infiltration rate and the water holding capacity of the soil thus increasing runoff. Smooth rollers pose the greatest danger in this regard as the others can leave a corrugated surface, which retains water on the surface allowing a longer time for infiltration to occur. However, the corrugations are small and will only reduce runoff from light rain. Rollers should generally not be used when there is a high erosion potential.

Rollers are used for the following purposes:
- Compacting the soil at various depths.
- Filling cavities.
- Breaking up clods.
- Breaking up surface crusts.
- Controlling the water movement in the soil by compacting the soil surface, which may increase or decrease evaporation depending on the circumstances as described above.
- Levelling the soil.
- Improving seed/soil contact and ensuring that the seeds are in good contact with the subsoil.
- Maintaining grassland.

Krause et al (1984) lists a number of advantages and disadvantages including the following advantages; good crumbling of hard clods if the correct tool is fitted; suitable for use on the heaviest soils; highly efficient; low draught requirement; simple sturdy construction and so minimal breakdowns; ease of construction, providing that casting facilities available. The disadvantages include the following; soil compaction cannot be avoided even when only crumbling is required; the soil's infiltration capacity is reduced, especially when a smooth roller is used; the drying process accelerated, but this may be desirable; a drying heavy soil may completely clog up an open roller; the soil erosion potential may be increased. Rollers are easy to operate but choosing the correct type and correct implement for the operation are very important.

Rollers are used mainly as trailed tillage implements and may be divided into the following types; smooth rollers; corrugated rollers; subsurface packers; and crust breakers. These are described below:

Smooth rollers:
Each unit consists of one long steel cylinder of 300 to 700 mm diameter, or up to 1500 mm diameter for special purpose rollers for use on pasture or marshy land. These rotate on an axle mounted on a frame with bearings. Usually operated as a single unit but more units staggered in two or more rows may be used, and this applies to all rollers. Compaction can be produced down to 15 cm. Smooth rollers produce good levelling and compaction of seedbeds for small seeds. However, they produce a soil surface more prone to erosion than do other types of rollers.

Corrugated rollers:
These are produced in the form of ring rollers, sprocket-wheel rollers, Cambridge rollers, and Croskill rollers. Each unit is made of a number of narrow cast iron rollers, or rings, of 350 to 650 mm, which rotate on an axle that is smaller than the central opening of the ring so as to allow relative movement between each ring. This allows the roller to follow uneven surfaces and also produces a self-cleaning action. On Cambridge rollers plain and toothed rings are mounted alternatively. On the Croskill or crowfoot roller the alternate rings are fitted with teeth and lateral lugs, which produces intensive crumbling, even on heavy soils. Corrugated rollers are used for their good clod crushing action.

Subsurface packers:
These consist of narrow cast iron wheels, usually with a wedge shaped rim and a diameter of 700 to 1100 mm, mounted so that they can rotate individually on a common axle, and spaced 100 to 180 mm apart. They can be mounted behind a plough or in combination with sowing equipment. They are used to compact the subsoil down to 20 cm.

Crust breakers:
These consist of tines or teeth mounted on the circumference of a smooth drum. They are used to penetrate and break the crust without damaging the seedlings, so allowing them to emerge through the crust.
Tillage intensity depends largely on the initial selection of the type of roller to be used. The depth of compaction is also partly determined by the type used and partly by the weight. The level of compaction can be increased partly by increasing the load on the rollers, by adding weights or filling them with water or sand, and by reducing the speed of operation.

The following technical details for tractor drawn rollers are based on Krause et al (1984):

- **Working width:** Up to 4.5 m with one-unit type and 9 m with more units.
- **Working depth:** Smooth and open rollers: Down to 15 cm. Subsurface packers: Down to 20 cm.
- **Average pressure produced:** Smooth rollers: 1 to 5 kN/m
  - Corrugated rollers: 1 to 5 kN/m
  - Packers: 2.5 to 5 kN/m
- **Travel speed:** 3 to 10 km/h.
- **Power requirements:** Low
- **Work rates:** Speed (km/h) x width/10 (m) ha/h.

5.3.2.6. **Levelling Implements**

Land smoothing and levelling is the practice of moving soil from high points to low points in a field, and was discussed in Section 4.1. When this is done on a larger scale, using landplanes or damscoops, it is usually defined as land-forming and is not classified as a secondary tillage operation. Land-forming implements are described in Section 5.3.3. However, it should be noted that many authorities use the terms smoothing, levelling and land-forming interchangeably.

All secondary tillage implements, other than ridgers, have a levelling effect on the soil as one of their secondary functions. However, the prime function of levellers is to level and smooth the soil surface.

**A. Levellers**

A range of levellers is shown in Figure ____ (Krause p 184, fig. 88, 89, 90). These include the 3-point hitch type and two drag types, the beam leveller and the hoop-leveller. These are very simple implements and in widespread use partly because of this. Animal drawn drag levellers are also in common use because of their simplicity and ease of local manufacture.

The leveller acts by pushing soil forward, depositing it in local depressions, and pulverising and compacting the surface layer. Capillary continuity with lower layers is broken and an insulating layer is produced on the surface that reduces water loss from deeper layers. In moist soils it also promotes a more uniform drying out of the soil. Accurate seed placement is not suitable for use without subsequent operations when there is significant wind or water erosion potential. The leveller is used for the following purposes:

- Levelling and smoothing of the soil surface.
- Crumbling and compacting the surface layer.
- Control of early weeds.
- Breaking up surface crusts.

In addition to the above its advantages include its simple and sturdy construction, and its ease of use and manufacture. Its disadvantages include the following; smearing on moist soils and some compaction of the soil both of which reduce infiltration capacity; transport of the
drag type implements can be difficult; fine soil particles are deposited on the surface, which combined with the smooth and level surface can result in high wind and water erosion potential. For the latter reason great care should be taken when using the leveller in tropical regions.

The majority of levellers are designed as dragged implements and the 3-point hitch system is not normally employed. A range of different type of tool units are attached to a trailed toolbar. The tools can be made of beams, boxes, hoops or chains and are described below:

- **Beam levellers:**
  These consist of one or more beams set perpendicularly to the direction of travel. They are connected to the toolbar and each other by chains or links. The beams are usually made of wood with a steel strip covering the leading edge.

- **Box levellers:**
  These permit weights to be added and the tool plane’s angle of attack to be adjusted, to control planting and compaction.

- **Hoop levellers:**
  Three or more hoops set in a staggered arrangement are attached behind the toolbar. The hoops may be made of steel or rubber tyres can be used.

- **Chain levellers:**
  Several chains are attached to the toolbar in various patterns.

The tillage intensity and depth can be controlled by adjusting the weight, the angle of pull, the angle of the working plane, and the speed of operation. The best results are achieved when the levelling operation is carried out at an angle to the direction of the previous tillage operation.

The following technical details for tractor drawn levellers are based on Krause et al (1984):

- **Working width:** Up to 8 m.
- **Working depth:** Up to 5 cm.
- **Number of tools:** Up to 12.
- **Weight:** 30 to 50 kg/m.
- **Speed of operation:** 8 km/h.
- **Power requirements:** Approximately 5 kW/m.
- **Work rates:** Speed (km/h) x width/10 (m) ha/h.

5.3.2.7.  **Ridging, Bed-shaping and Pot-holing Implements**

The tillage implements described previously, with the exception of the leveller, are designed primarily to alter the soil structure, to facilitate the incorporation of other substances into the soil, or to destroy weeds and pests. In contrast, the primary objective of the ridging, bed-shaping and pot-holing implements is to shape the soil surface, with the previously listed objectives usually being secondary in importance.

Ridge and furrow tillage systems are frequently used in the tropics and subtropics to reduce erosion and promote soil and water conservation, to implement furrow irrigation systems, and to facilitate harvesting. The ridges and furrows should always be built with gentle gradients so that the speed of flow within the furrow is not erosive. The tied-ridging system, in which dams are built at regular intervals in the furrows, is used to further reduce runoff from rainfall and high intensity sprinkler irrigation systems. The ridging system was originally developed in the humid regions to overcome waterlogging problems by planting on the raised ridges. The ridging and tied-ridging system is described in Section 3.1.2.3.

Beds are basically broad-based ridge and furrow systems. They are also used for soil and water management, in irrigation systems and in some controlled traffic systems.
A. Ridgers

A range of ridgers is shown in Figure ___(@ Krause 1984, p 204, fig. 103, p 218 figs. 109, 110, 111). There are three main types of ridgers, viz.; the rigid type; the mouldboard type, or Lister plough; and the disc type, or disc bedder. Ridgers are suitable both for tractor draught and animal draught purposes, although generally disc type ridgers are not suitable for animal draught.

With the mouldboard type of ridger body the share penetrates the soil and the soil is transported along its breast and wings to the top of the ridge. With disc type implements the discs are driven by the soil and cut into the soil and push and roll it upwards to the top of the ridge. For all types the shape of the ridge formed is determined partly by the depth of operation, the shape of the ridger body, the speed of operation, and the angle of repose of the soil. The last factor depends on the soil's texture and moisture content. Conversely, these are the main factors that should be considered when selecting the type and shape of the ridger body, and its adjustment, for the required size and shape of the ridge. When the ridger is used for weeding existing ridges the weeds and soil are deposited on the top of the ridge. Subsequent intra-row weeding is often required if the soil does not adequately bury the weeds on the top of the ridge.

The ridger is used for the following purposes:
- Building ridges for:
  - Soil and water conservation systems.
  - Furrow, strip and border irrigation systems.
  - To facilitate growth of some root crops.
  - To facilitate ease of harvesting of some crops.
- Digging furrows for drainage.
- Covering seed and tubers.
- Covering manure, fertilizers, and herbicides in furrows, or in rows and on ridges.
- Control of weeds on ridges.
- Rebuilding ridge and furrow systems.

The main characteristics and differing uses of the mouldboard and disc type ridger bodies are described below:

Mouldboard type ridger bodies:
As shown in Figure ___(@ Krause p 204, fig. 103 and p 218, fig. 109) there are several different types of mouldboard ridger bodies designed for different speeds of operation, different soil conditions, different means of adjustment of their wings, etc. Mouldboard type ridger bodies produce a relatively smooth furrow, depending on the condition of the soil. In moist soils the shape of the wings of some types can result in smearing of the soil. The mouldboard ridger is often preferred for crop maintenance operations, weeding and re-ridging, because on some models the shape and means of adjustment is such that the wings can be adjusted to the existing ridge shape so that they cut just under the soil surface along the whole of the side of the ridge. This is important for efficient weeding, to reduce the draught power requirement, and particularly so that the ridger does not cut into the roots of the crop plants.

Disc type ridger bodies:
As shown in Figure ___(@ Krause p 219, figs. 110 and 111) disc ridgers may be made up of only two discs or two gangs of discs. The latter give a finer topsoil than the former which leave a rough furrow. Disc ridgers produce a ridge that is relatively level and loose with a high infiltration capacity. These may require compaction, for moisture control or seedbed requirements, and this operation is usually performed in a separate pass. Notched discs should be used when plant material or hard soils make penetration difficult. A notched disc performs more satisfactorily than a mouldboard ridger on firm moist soil, while ridgers with two or more
discs per gang may clog up on moist adhesive soils. When large ridges are to be formed then different sized discs are required with the larger discs running along the bottom of the furrow. The disc ridger is used principally when harvest residue, stones or roots are likely to be encountered. The disc ridger is also preferred for cotton production.

The ridger is one of the most important implements for furrow, strip and border irrigation systems. Disc ridgers are recommended when short furrows have to be formed on steep slopes. This is because the disc ridger creates a loose crumbly furrow that reduces the flow velocity and increases the water infiltration rate. Mouldboard ridgers are recommended for the construction of long furrows with slight gradients. This is because they create a clean furrow that results in a higher water velocity, reducing the possibility of overflow of the ridge, and a lower infiltration rate, allowing irrigation water to reach the end of the furrow.

Mouldboard and disc ridgers are usually mounted on toolbars attached to the 3-point system on tractors, or sometimes in the front of tractors. Their attachment to a toolbar allows them to be moved laterally to alter ridge spacing. The height of the ridge, or depth of operation, is altered by altering the height of the toolbar or the support wheels or the setting of the spring load. To reduce the draught energy required the ridger body should be chosen and adjusted to form a ridge whose initial slope does not exceed the angle of repose of the soil. The angle of repose of fairly dry soils varies according to soil texture from roughly 30 to 40 degrees. On mouldboard ridgers the initial shape of ridger body chosen is the most important factor, although the wings can often be adjusted. The wing tips should usually be high rather than low to minimise draught and to be appropriate for maintenance work. On disc ridgers the disc angle can be adjusted in the same way as for disc ploughs. When the disc angle is increased more soil is moved and a wider furrow and higher ridge made. The setting of the tilt angle determines the initial slope of the ridge. The height of the ridge also increases with speed as the soil is thrown further. The best working speed is 5 km/h. Increased crumbling can be achieved by increasing the number of discs in each gang. Other selections for disc ridgers have already been described.

The depth control of animal drawn mouldboard ridgers is by means of the depth control clevis as used on the animal drawn mouldboard plough.

The following technical details for tractor drawn ridgers are based on Krause et al (1984):

- **Working width:** Row distance per body: Up to 1 m. Total width: Up to 9 m.
- **Working depth:** Up to 28 cm.
- **Angles:** Mouldboard ridger: Share: 30 to 40 degrees. Wings: 30 to 50 degrees. Disc ridger: Disc angle: 0 to 50 degrees. Tilt angle: 0 to 45 degrees.
- **Speed:** Standard mouldboard and disc bodies: 4 to 6 km/h. High speed mouldboard bodies: 6 to 10 km/h.
- **Power requirements:** 5 to 15 kW per body
- **Work rates:** Speed (km/h) x width/10 (m) ha/h.

**B. Tied-Ridging Units**

Tied-ridging units are used to tie the ridges to each other by means of forming dams in the furrows. This holds the water where it falls producing an even distribution of water over the field and also prevents runoff except during very heavy rainfall. The dams are constructed to a height of one half to two-thirds the size of the furrow so that during heavy storms they overflow rather than the ridge which could result in severe erosion.

A range of tied-ridging units is shown in Figure ____(@ Krause 1984, p 203, fig. 102 +
Matthews p B3). They operate by dragging soil along the bottom of the furrow until sufficient has been collected to form a dam, at which point the soil is deposited. Several alternative types exist. The simpler units consist of a shovel on a frame that is lifted at regular intervals by an eccentric support wheel. An even simpler animal drawn version consists of a disc or shovel attached to a pole that is lifted by the operator at regular intervals to deposit the accumulated soil and form the dam. Other versions consist of three or four paddles on a rotor and the rotor is tripped at regular intervals to deposit the soil. The tripping can either be operated hydraulically or in some models by the weight of the soil collected.

When a tractor is operated in a field with tied ridges the ties are frequently ploughed out in front of the tractor's wheels by means of front mounted ridger bodies. However, the ties have usually been sufficiently flattened by the time that the next field operation is required so that this is not necessary.

C. Bed Shapers

Bed shapers are used to consolidate ridge and furrow systems made by ridgers, or to alter the shape of the initial ridge into a ridge or bed shape more suitable for a specific irrigation system. A range of bed shapers is shown in Figure ___(@ Krause 1984, p 225). These include simple press wheels running between the ridger bodies over the crest of the ridge, to profiled cone-shaped rollers and trailed profiled bodies.

The bed shaper is useful for soil and water management, for distributing and conducting water and for stabilising ridges to protect them against heavy rainfall. They are used for the following purposes:

- Geometric shaping of ridges and beds.
- Compacting the surface soil.

The bed-shaper smooths and compacts the surface of the furrows and so increases the speed of water flow. It can be used after disc ridgers for this purpose to allow better distribution of the water in long irrigated fields with slight gradients.

D. Pot-holers

Pot-holers are used to promote soil and water conservation. They are used to scoop out depressions between the crop rows that accumulate rainwater on the soil surface, thus allowing greater time for infiltration and reducing runoff. A range of pot-holers is shown in Figure ____(@ Photographs)

Pot-holers are very similar to tied-ridging units. They consist of a shovel mounted on an eccentric wheel that scoops out depressions at regular intervals. Animal drawn pot-holers can easily be made by attaching a disc or shovel to a pole, which is either lifted by the operator or mounted on an eccentric wheel. When used with tractors the rows to be used by the tractors wheels for subsequent operations are not pot-holed.

A major advantage of potholing over tied-ridging is that the crop can be planted on the flat, which eases some mechanisation operations and avoids possible germination problems of planting on top of ridges in arid and semi-arid areas. However, tied-ridging is much more effective for soil and water conservation than potholing, because much more water can be held on the surface with the former system.

5.3.2.8. Manual Tillage Implements

As shown in Section 5.2.1 a healthy and well fed human adult has a sustainable power capability of about 0.07 to 0.1 kW and can exert a pull of around 0.1 kN. Due to this low power
capability it is very important that efficient manual tools are selected, i.e. the tools should be as light and easy to operate as the job requires, and they should allow a high workrate. Furthermore, both from the health and safety point of view as well as maximising work output, they should be designed to minimise fatigue and strain and possible injury to the operator. An important advantage of all manual tillage implements is that they are cheap and can also be manufactured locally in rural areas with only basic manufacturing facilities. The manual tillage implements discussed in this section are hoes, rakes and wheeled weeders.

A. Hoes

Hoes are used primarily for secondary tillage, but are also used for primary tillage when tractor and animal draught power is not available. They are mainly used for weeding, loosening the soil between crop rows and for soil and water conservation measures such as ridging and pot-holing.

A range of hoes is shown in Figure ___(@ Agritex AP4 1.6 + 2.7). The main criteria used in the classification of hoes are the weight of the hoe, the shape of the blade, and the length of the handle. The following main types of hoes are described:

- **Tang hoe:** A medium weight, straight-edged blade, medium-length handled hand hoe, most suitable for loosening light soil. The operator works in a slightly bent position.
- **Heart-shaped tang hoe:** A medium-weight, round-edged blade, medium-length handled hand hoe, most suitable for making pot-holes. The operator works in a slightly bent position.
- **Ring hoe:** A heavy-weight, straight-edged blade, medium-length handled hand hoe, most suitable for loosening heavy or very compacted soil. The operator works in a slightly bent position.
- **Sunken-head hoe:** A very heavy-weight, straight-edged blade, short to medium-length handled hoe, most suitable for loosening heavy soil and for making ridges. The operator works in a slightly bent position.
- **Swan-neck hoe:** A light-weight, straight-edged blade, long handled hoe, most suitable for weeding in light or soft soils. The operator works in an upright position.

When loosening soil to improve infiltration a depth of around 8 cm should be aimed for. To avoid damage to the crop roots a distance of 5 cm from the crop should not be worked. To achieve optimal loosening effect the soil should not be wet when the operation is carried out.

Ridging or re-ridging is carried out by the operators moving sideways along the ridge and pulling the soil from the furrow on the far side of the ridge towards themselves to the top of the ridge. On each pass along a row, half the ridge is made, so for each ridge two passes along a row are required.

Pot-holing involves making holes 15 cm deep by 40 cm long between the rows, leaving a heap of soil in the row at the operator's end of each hole. After completing a hole the operator moves forward one pace in the row to dig the next hole.

Mechanical weeding involves either pulling out the weeds, cutting the above surface part of the weed plants from their roots roughly 5 mm below the soil surface, or covering the entire weed with soil. When whole weeds are left on the surface to die it is important to remove all soils from the roots, and to carry out the operation when the soil is dry and no rain is expected for the next few days. The swan-neck hoe is the best hoe to use for weeding
providing the soil is soft as it allows a more upright working position, is lighter to use and more manoeuvrable, and its use can result in a significantly higher work rate. If the soil is not light or soft one of the straight-edged, heavier hoes with a medium length handle should be used. The hoe is pulled towards the body, keeping the blade almost flat on the ground so that penetration is limited to around 5 mm. A scraping rather than a chopping motion is used when only weeding is being carried out. When soil loosening is carried out at the same time as weeding then the weeds need to lifted out by hand or covered to destroy them.

B. Rakes

Due to the light weight of the rake head long handles can be used which allow an upright working position, good manoeuvrability and a high work rate.

Rakes are primarily used to lightly till the soil to break up crusts and improve infiltration, and for weeding. However, very shallow tillage can promote erosion by leaving a shallow loose erodible surface over a hard surface. They are also used to break up crusts over germinating seeds to improve aeration and to allow the emergence of the plant through the surface layer. They can only be used on light soils.

C. Wheeled Weeders

A range of wheeled weeders are shown in Figure ___ (@ Photographs) They consist of blades which are designed to run roughly 5 mm under the soil surface to sever the above surface part of the weed plant from its roots. The blades are attached to a wheel and/or skid to control depth.

A much higher rate of work can be achieved with these weeders compared to hand hoes because the depth of operation is easier to control and the implements are also more stable. This latter aspect also allows a larger blade to be used than on a hand hoe that further increases the rate of work. Rake attachments can also be used on this implement that give better control of the depth of operation when breaking crusts over germinating seeds.

5.3.3. Land Forming Implements

Land forming implements are very important for irrigated agriculture and are also commonly used in dryland farming systems. They are basically soil moving implements rather than soil conditioning implements. The two types most commonly used, viz. landplanes and damscoops, will be described in this section.

In irrigation systems, and especially flood irrigation systems, it is very important that the field has a uniform slope, in order to enable a uniform distribution of water over the field to be achieved through good water management systems. Even in rainfed farming systems it is desirable to have fairly uniform gradients, without depressions or high spots, to achieve a uniform distribution of rainwater over the field. Another important use of landplanes and damscoops is in the construction of drainage and conservation works.

5.3.3.1. Landplanes and Damscoops

A range of landplanes and damscoops are shown in Figure ___(@ Krause p 212, fig. 106 + AP3 p 2.12, 2.13 + AP3 p 2.27, 2.28). Both of the implements are sometimes called landplanes and sometimes also called land levellers or land smoothers. Landplanes and damscoops are available in both tractor drawn and animal drawn versions.

The blade of the landplane may be fixed at right angles to the direction of travel on
some models, or on larger and more complex models may be adjustable so that soil can be moved laterally. The damscoop differs from the landplane in that it has a container to carry the soil over short distances. Small damscoops are available for animal draught purposes and are excellent implements for the construction of conservation works.

The landplane acts by pushing soil above the blade's cutting edge forward and depositing it in depressions as it is drawn across these. Landplanes with blades that can be angled to the direction of travel can move the soil forward and laterally from high points to low points and can also be used in the construction of conservation works.

The damscoop operates by scooping up soil from one area and depositing it in another some distance away under the control of the operator, whether this be a raised area or a low area.

The landplane and damscoop are used for the following purposes:

- Moving the soil to level the soil surface.
- The construction of irrigation, drainage, conservation works and terraces.
- Construction of small earth dams, (usually damscoops only).
- Road building.

When landplanes are to be used without subsequent tillage it is important that the soil should be dry enough to avoid smearing. Smaller implements may be mounted to the tractor's 3-point hitch system whereas larger implements are usually trailed. On tractor drawn landplanes support wheels are essential and for the best levelling action the blade on the landplane should be midway between the hitch point and the supporting wheels, and these should be as far apart as possible. The working depth is adjusted manually or hydraulically by one or more guide wheels.

Tractor drawn damscoops are semi-mounted or trailed so that all or most of the weight of the soil is carried by the support wheels. The scooping up and depositing of soil is controlled hydraulically. The blade or blade edge on both the landplane and the damscoop are replaceable.

The means of operation of an animal drawn damscoops is shown in Figure ___(@ AP3 p 2.25, fig. 2.13). They have two handles at the rear that are used to control the cutting angle of the blade while scooping up soil. When sufficient soil has been collected the handles are lowered so that the damscoop is dragged along on its base without any of the weight having to be taken by the operator. To deposit the soil the handles are raised high while the scoop is still being pulled forward so that the blade trips the scoop over. It is important that the handles and the points of attachment to the draught source are well designed to minimise the effort of operation and control. The blade edge should be replaceable and additional skids should be welded to the underside of the damscoop to increase the life expectancy of the implement.

The means of operation of an animal drawn landplane is shown in Figure ___(@ AP3 p 2.27, fig. 2.15). The handle controls the angle of the blade and by standing on the plank weight is added to increase penetration and to prevent the whole implement from tripping over. For operation in hard soil the handle is held back to provide a greater cutting action and the rear plank is stood on near the blade to increase penetration. For operation in soft soil the handle is held forward and the board is stood on at the rear to reduce weight on the blade. To deposit the soil the handle is moved further forward to allow the soil to pass under the blade.

The construction of conservation contours using manual labour alone is a highly labour intensive operation and is an important reason why their construction and maintenance is often neglected. If tractor draught power is not available and animal draught power is, then animal drawn damscoops can play an important role in the promotion of conservation works. A detailed description of the use and field implementation of the animal drawn damscoop is given.
The following technical details for tractor drawn landplanes and damscoops are based on Krause et al (1984):

- **Working width**: 1.5 to 3 m.
- **Working depth**: 5 to 40 cm.
- **Volume of soil moved**: 1 to 2.5 cubic metres.
- **Speed of operation**: Landplanes: 3 to 6 km/h.
- **Power requirements**: 15 to 50 kW/m.

### 5.3.4. Field Implementation of Tillage Operations

The field implementation of primary and secondary tillage operations should be carried out in a well planned and systematic manner for several reasons. These reasons include the following:

- To minimise the cost of their implementation in terms of labour, energy and equipment.
- To make the best and sustainable use of the arable land available for crop production.
- To achieve the full objective of the tillage operation being implemented, including the importance of completing the operations in a timely manner, so as to maximise crop yields. The objectives of tillage were discussed in detail in Section 5.3.

One commonly used term that needs to be defined is field efficiency. Field efficiency is the percentage of the time that an implement is doing useful work while it is being operated in the field, i.e. headland turning and travelling time is excluded.

In order to implement tillage operations in a well planned and systematic manner the following points should be considered and incorporated into the plan:

- The field should be stumped, cleared and levelled so that obstacles to the efficient and effective implementation of tillage operations are minimised.
- Tillage operations are generally costly in terms of labour, energy and equipment, and this is particularly true of ploughing. These operations should only be carried out when necessary in terms of their cost to benefit performance, which should include their effect on the long-term sustainability of the crop production system.
- Tillage operations should always be selected and implemented in line with good soil and water conservation practices. With regards to implementation this means that primary and most secondary tillage operations being carried out on slopes greater than 2% should be carried out across the slope. This is because tillage operations generally create small ridges and furrows and if these are built across the slope they trap the water and reduce the speed of runoff down the slope. This increases infiltration, which also reduces runoff, and the reduced amount and speed of runoff reduces soil erosion. This is particularly important for those tillage operations that leave sizable ridges and furrows, such as ploughing and ridging. Tillage operations should generally not be conducted on slopes greater than 12% due to the high risk of erosion, and on highly erodible soils the maximum slope is lower.
- The appropriate implement, the implement setting, speed of operation and time required, soil conditions, etc., need to be selected so that the overall objective of the tillage operation can be met. These aspects were dealt with in Sections 5.3.1 and 5.3.2.
- Some implements, viz., the mouldboard and disc ploughs, are in a sense earth-moving implements and move the soil to one side. If the same ploughing pattern is used each year, i.e. moving the soil in the same direction each year, this will lead to the formation of ridges on one side of the field and depressions on the other side. This will adversely affect the drainage and water storage characteristics of the field as well as reduce the area available for crop production. Ploughing patterns should therefore be alternated from year to year to maintain the soil profile in the field.
- To use all the available arable land for crop production the tillage operation should
reach the edges of the field or natural boundaries. The tillage operation should leave well-defined boundaries, with no portion of the field left untilled or tilled more than once.

- The operations should be carried out such that the path used by the draught source does not go over soil already tilled, as this will compact the soil and reduce the effectiveness of the tillage operation.
- The operations should be planned to minimise the amount of unproductive time spent turning and travelling on headlands, i.e. high field efficiencies should be achieved. However, for animal draught the time spent turning at the headland is used as a necessary short rest period and these periods should not be too far apart.
- With the exception of broad-based conservation contours conservation works should not be tilled or driven over, especially when new. If they are tilled the loose soil will be more prone to erosion. Although grassed waterways can be used as headlands for turning they should not be used as roads, as the tracks left will lead to erosion.
- The accuracy and ease of subsequent operations, such as planting and inter-row cultivation, depend on good primary tillage and as few opening and finishing furrows as possible. This is also particularly important for tillage in flood irrigation systems. Subsequent operations need evenly spaced parallel lines that follow the contours, or go in straight lines on flat lands. Because it is easier to plant the ploughed land in the direction of ploughing rather than across the ridges, ploughing should be planned to allow planting lines to follow the ploughed furrows as closely as possible.

The above points apply both to primary and secondary tillage operations, but particularly to the former.

### 5.3.4.1. Field Implementation of Primary Tillage Operations

The main primary tillage implements are the mouldboard, disc, chisel and sweep ploughs; the rotary cultivator; the paraplough; and the subsoiler. These implements were described in detail in Section 5.3.1 including their uses, operational characteristics and their adjustments. The depth of tillage operations were discussed in relation to the various soil, environmental and economic parameters throughout Section 2 and particularly in Sections 2.1.2.5, 2.4.1.1 and 2.4.5. This section will deal primarily with the required layout of the field for the implementation of primary tillage operations and the patterns of use of the implements within the field.

Of the primary tillage implements only the mouldboard and disc ploughs move the soil to one side during their operation and this is due to their good soil inverting properties. Due to the reasons listed in the previous section, as well as because mouldboard and disc ploughs both move the soil to one side and leave fairly large ridges and depressions, their use in the field in particular needs to be well planned and carried out systematically.

The systematic procedures used for mouldboard and disc ploughing should generally also be used for all other primary and secondary tillage operations. This is due to the requirement that the tillage operations should be carried out such that the path used by the draught source does not go over soil already tilled, and because most tillage implements leave small ridges and depressions. However, the rotary cultivator, which does not leave marked ridges and depressions, can also be operated up and down slopes greater than 2%. Care should however be taken on the use of the rotary cultivator in the tropics and arid regions, as discussed in Section 5.3.1.7.

The planning and systematic implementation of primary tillage operations outlined in this section will be based on the mouldboard and disc ploughs for the reasons given above. This section is based closely on the AGRITEX Training Manuals AETC, Animal Power 2, 1986, and AETC Tractor Power 2, 1987, which should be referred to if a full training manual format is required.
A. Ploughing Using Mouldboard and Disc Ploughs

There is very little fundamental difference in the planning and implementation of ploughing operations between the mouldboard and disc ploughs, and between the use of animal draught power and tractor draught power. For the sake of simplicity this section will be primarily based on the use of animal draught power and the mouldboard plough, and where these differ from the others they will also be shown or described.

Preparations necessary on a field are determined by the natural state of the area, or the extent of previous work on it. The steps in field preparation are as follows:

1. Determine the boundaries of the field.
2. Draw a sketch of the field, showing the boundaries, e.g. roads, fences, waterways, neighbour's field; the dimensions; slope; obstacles, e.g. rocks, trees, anthills; and conservation works.
3. Stump and clean the field, clearing it of trash. Stumps should be dug out to at least 45 cm below the surface. For good burial of crop residues, grass, weeds, etc. during ploughing these should not exceed 15 cm in height. If they do they should be cut down prior to ploughing.
4. Level the field by removing anthills and filling large holes.
5. Establish or repair conservation works.

On virgin land all five preparation steps should be carried out. On fallow land it may only be necessary to carry out clearing and repairs to conservation works. On recently ploughed land no preparation may be required unless poor ploughing practices were previously used, in which case some levelling and the repair of conservation works may be required.

The ploughing pattern used is largely dependent on whether a one-way or reversible plough is to be used. One-way ploughs, which turn the furrow slice to one side only, usually to the right, and reversible ploughs, which can turn the furrow slice towards the same side of the field even though the plough travels in opposite directions, were defined in Section 5.3.1.1., and their main advantages and disadvantages were also given there.

The main terms used in the planning and implementation of ploughing operations are defined below:

- **Field**: Piece of arable land used for crop production demarcated by natural boundaries or boundaries between different owners.
- **Land**: Part of field ploughed using the same pattern.
- **Headland**: Area left for turning after leaving a furrow and moving to start the next furrow.
- **Ploughing system**: The overall system by which a field is ploughed.
- **Ploughing pattern**: The pattern by which a land or field is ploughed. The pattern is alternated each year to retain the soil profile.
- **Gathering**: A ploughing pattern for one-way ploughs starting in the centre of the land and moving the soil towards the centre.
- **Casting**: A ploughing pattern for one-way ploughs starting at the edges of the land and moving the soil towards the edges.
- **Reversible ploughing**: A ploughing pattern for reversible ploughs starting at one edge of the field and moving the soil towards one of the edges.
- Opening and closing furrows:
  A method of opening and closing the first and last furrow in a land or field so as to cover weeds and minimise weed regeneration and to maintain the soil profile.

A.1. Components of Ploughing Systems

The type of ploughing system to be used in a particular case depends primarily on the slope of the field and whether the plough is a one-way or reversible plough, and these will be described later. Ploughing systems have some or all of the following components that will be described in detail:
- Main direction ploughing, which is determined by the shape or slope of the field.
- Headlands, which are determined by the need for a turning space at the ends of the furrows.
- Lands, which are determined by the size of the field but are only required for one-way ploughs.
- Patterns of ploughing, which are determined by the need to maintain the soil profile, i.e. to keep the soil surface level over the years.
- The type of opening and closing furrows, which are determined by the ploughing pattern chosen.

A.1.1. Main Direction of Ploughing

The main direction of ploughing in a field of less than 2% slope is generally along the longer side of the field so as to minimise the time spent turning. However, when using animal draught power, the maximum length of furrow should not exceed 150 m. This allows the animals a brief rest while turning at the headlands. For large fields with one side longer than 150 m it may therefore be more practical to use the shorter side of the field when using draught animals.

The main direction of ploughing on a slope between 2% and 12% must be across the slope, or parallel to the conservation contours, even if this means ploughing along the shorter side of the field.

A.1.2. Headlands

Headlands are areas left at the end of fields to allow turning and travel between ploughing runs. Where the boundary at the end of the field is a barrier, such as a fence, then the width of the headland is usually 6 m for draught animals and 6 to 12 m for tractors and implements depending on their size. Where the boundary is open the headland can be reduced to 2 m for animal draught without disturbing the land which is not to be cultivated. For tractor draught the headland size will depend mainly on the distance between the first and last plough body.

Headlands consist of areas that may or may not be cropped. The latter may be existing roads or waterways, or adjacent uncultivated areas. Headlands on fields with a slope greater than 2% are also not ploughed. This is because the main furrows run across the slope and if the headlands were ploughed these furrows would run down the slope that would lead to a high erosion potential. These headlands are left grassed and wherever possible roads or waterways are used so as to maximise the cropped area. This is shown in Figure ___(@ AGRITEX AP2 p 4.14, fig. 4.7).

If headlands on fields on slopes of less than 2% are to be cropped, e.g. when the field is fenced and no other area is available for headlands, then the headlands are ploughed after the completion of the main field. When a one-way plough is used then strips along the side of the field of the same width as the headland are also left, and these are ploughed at the same time as the headlands. This is shown in Figures ___(@ AGRITEX AP2 p 4.12, figs. 4.4., 4.5,
A land is a part of a field ploughed using the same pattern. The concept was developed for use with one-way ploughs to improve their field efficiency. Large fields are divided into smaller sections, viz. lands, so that a minimum amount of time is spent on the headlands between runs. The size of lands is dependent on the size of the field and whether draught animals or tractors are to be used, as described below:

- **Animal draught power:**
  - A land is an area that can be ploughed with draught animals in one day, roughly 0.2 ha.
  - The length of the furrow is limited to 150 m, as animals work hard when ploughing the furrow and they relax when moving on the headland.
  - The width of the land should not exceed 25 m to minimise the time spent on the headlands.

- **Tractor draught power:**
  - The length of the furrow is only limited by the field size or conservation works, etc. The longer the furrow the higher the field efficiency.
  - The width of the land is dependent on the number of plough bodies:
    - 2 to 3 bodies: 30 to 45 m.
    - 4 to 5 bodies: 45 to 60 m.

The number of lands should be kept to a minimum as each land requires an opening and finishing furrow, which will be described in a later section. These take more time to make than full depth ploughing. They may also have to be levelled after ploughing, thus taking up more time. Headlands along the direction of the slope are not ploughed.

Lands, once chosen, have to be maintained. Opening and finishing furrows will always be in the same place, but alternated from year to year. This is to ensure that the soil moved in one direction one year is moved back the next so as to maintain a level surface.

**A.1.4. Patterns of Ploughing**

The ploughing pattern describes the sequence and direction in which the soil is moved. In order to maintain the soil profile over the years the ploughing pattern is alternated from year to year. There are three types of ploughing patterns, viz.; gathering and casting, which are implemented with the one-way plough; and reversible ploughing, which is implemented with the reversible plough. These are defined below, and shown in Figure ___(@ AGRITEX AP2 p 4.19,20,21, figs. 4.8, 4.9, 4.10):

- **Gathering pattern:**
  - Ploughing starts in the middle of a land, turning right at the headlands, and continues clockwise towards the side of the land, finishing on both sides. The furrow slice is turned towards the centre.

- **Casting pattern:**
  - Ploughing starts at one side of the land, turning to the left at the headlands, and continues in an anti-clockwise direction inwards from the sides to the middle of the land where the finishing furrow is made. The furrow slice is turned away from the centre.

- **Reversible ploughing pattern:**
  - Ploughing starts at one side of the field and continues in parallel furrows to the other side of the field. The furrow slice is turned away from the side of the field on which the finishing furrow is made.
  - On steeper slopes ploughing may start at the bottom of the slope on most years with the soil being thrown up the slope to compensate for soil eroding down the slope.
A.1.5. Opening and Closing Furrows

Specific procedures are used to open and close the first and last furrow in a land or field so as to minimise weed regeneration and to maintain the soil profile. There are two main types of opening furrows and one main type of closing furrow, and these are determined by the ploughing pattern chosen and the type of plough used.

All ploughing starts with an opening furrow and ends with a finishing furrow. For the reversible plough these furrows are always at the edge of a field where they generally do not present a problem for subsequent tillage operations. However, where these furrows are along the bottom contour of a land, it is very important that they do not prevent runoff from running into the contour and act as the channel themselves. This could result in increased erosion losses as they are not protected by a grass cover. The one-way plough uses ploughing patterns which can result in ridges or furrows in the middle of the lands if specific procedures are not used to make them. These ridges and furrows can interfere with subsequent tillage operations and can alter the drainage and water storage characteristics of the field.

The types of opening and finishing furrows are listed below together with the ploughing system and type of plough with which they are used, and are then described in detail:

- **Single opening furrow:**
  - Casting ploughing system with one-way plough.
  - Reversible ploughing system with reversible plough.

- **Double opening furrow and crown:**
  - Gathering ploughing system with one-way plough.

- **Single finishing furrow:**
  - Gathering ploughing system with one-way plough.

- **Double finishing furrow:**
  - Casting ploughing system with one-way plough.

A.1.5.1. Single Opening Furrow

The single opening furrow is used with the casting ploughing system with the one-way plough, and the reversible ploughing system with the reversible plough. Ploughing is started at the edge of the land or field. When starting to plough with the casting system next to a land that has been gathered, the last open furrow of the gathered land is used and no opening furrow is required.

The procedure to be followed with a single animal drawn plough is shown in Figure____(@ AGRITEX AP2 p 5.4, fig. 5.1.a+b) and described below:

1. If the opening furrow is straight then set the sighting pegs, if the furrow follows contour lines which are not straight then place pegs at 10 to 20 m intervals parallel to contour lines.
2. For the first run, set the plough to cut below the root zone at less than half the full ploughing depth, throwing soil inside the field.
3. For the second run, set the plough to plough slightly deeper and plough the first furrow slice back into the open furrow.
4. Carry on ploughing in the same way and increase depth until full ploughing depth is reached.

A good opening furrow should have a good graduation across furrows and evenness along furrows and should have achieved good burial.

When a single furrow opening is to made with a multi-bodied tractor drawn disc plough, then on the first run the plough is adjusted, by tilting it to the rear, so that the first furrow is cut
by the rear body of the plough. On the second run the plough is again readjusted, by slightly reducing the tilt, and the front plough body is used to turn the first soil slice back into the open furrow, with the other plough bodies cutting increasingly deeper furrows. When the full ploughing depth has been reached on the last furrow then the plough is adjusted to operate in its normal horizontal position.

A.1.5.2. Double Opening Furrow and Crown

The double opening furrow and crown is used with the gathering ploughing system with the one-way plough. With this system ploughing is started in the centre of the land and the aim is to achieve an even surface with no unploughed land underneath. The procedure involves first of all making a double split opening and this is then followed by making a crown.

The procedure to be followed with a single animal drawn plough is shown in Figure___(@ AGRITEX AP2 p 5.6 to 5.10, figs. 5.3 to 5.7.) and described below:

Procedure for making a double split:
1. Set sighting pegs for straight furrow, or place pegs parallel to contour lines.
2. For first run, set the plough to cut below the root zone at less than half the full ploughing depth.
3. For the second run, set the plough to plough slightly deeper than the first run. The soil should be thrown in the opposite direction to the first run. The left side draught animal should walk in the furrow to make it easier to control the plough.

Procedure for forming a crown:
1. For the first run, set the plough to cut slightly deeper than the double split, but the plough must be able to turn the extra soil left from forming the split. The right side draught animal should walk in the first furrow of the split.
2. For the second run, the plough is kept at the same depth and the two furrow slices should just meet to form the first base of the crown formation. The right side draught animal should walk in the remaining furrow.
3. On the third run, set the plough deeper and increase the width of cut if necessary. Use the same setting for the fourth run to maintain symmetry. Aim to reach full ploughing depth on the fifth and sixth runs.

A good crown should have a good graduation across furrows and evenness along furrows and should have achieved good burial.

When a double opening furrow and crown are to made with a multi-bodied tractor drawn mouldboard or disc plough, then on the first run the plough is adjusted, by tilting it to the rear, so that the first furrow is cut by the rear body of the plough. On the second run the plough is again readjusted, by slightly reducing the tilt, and the second plough body is run in the first furrow which was cut. This means that the first plough body cuts a new furrow, and if there is a third plough body it moves the first furrow slice back into the first furrow that was cut. The soil is moved in the opposite direction to the first run. The crown is then formed by two runs in which all the plough bodies are ploughing new furrows, which results in all the centre furrows being filled. For this operation the tilt of the plough is again reduced. When the full ploughing depth has been reached on the last furrow then the plough is adjusted to operate in its normal horizontal position.

A.1.5.3. Single Finishing Furrow

The single finishing furrow is used with the gathering ploughing system with the one-way plough and the reversible ploughing system with the reversible plough, and is made on the edges of the land or field. A finishing furrow is not used with the gathering system if the adjoining land is to be ploughed in the casting pattern, as it will then be used as the new
opening furrow.

The procedure to be followed with a single animal drawn plough is shown in Figure ___ (@ AGRITEX AP2 p 6.4, fig. 6.1.) and described below:

1. For a land that has been properly planned and pegged, and an even width of cut maintained during ploughing, then a parallel strip of unploughed ground should be left when reaching the edge of the field. Check when 2 m are left, so that corrections can be made before the final recommended width of 80 cm is reached, i.e. four runs using a 20 cm plough.
2. Reduce the depth of ploughing evenly from full depth to half that over four runs.

A good finishing furrow should be narrow and shallow and clean with no unploughed portions along its length. There should be a good graduation across furrows and evenness along furrows.

When a single finishing furrow is to be made with a multi-bodied tractor drawn mouldboard or disc plough, then the plough should be adjusted, by tilting it towards the front, so that the plough depth is reduced from full depth by about 4 cm on each plough body during the last run or two.

A.1.5.4. Double Finishing Furrow

The double finishing furrow is used with the casting ploughing system with the one-way plough, and is made in the middle of the land.

The procedure to be followed with a single animal drawn plough is shown in Figure ___ (@ AGRITEX AP2 p 6.6 to 6.9, figs. 6.3 to 6.8) and described below:

1. For a land that has been properly planned and pegged, and an even width of cut maintained during ploughing, then a parallel strip of unploughed ground should be left when reaching the edge of the field. Check when 3 m are left, so that corrections can be made before the final recommended width of 160 cm is reached, i.e. eight runs using a 20 cm plough.
2. Reduce the depth of ploughing evenly from full depth to half that over eight runs as shown in the diagram.

A good finishing furrow should be narrow and shallow and clean with no unploughed portions along its length. There should be a good graduation across furrows and evenness along furrows.

When a single finishing furrow is to be made with a multi-bodied tractor drawn mouldboard or disc plough, then the plough should be adjusted, by tilting it towards the front, so that the plough depth is reduced from full depth by about 4 cm on each plough body during the last two or four runs.

A.2. Ploughing Systems

The type of ploughing system to be used in a particular case depends primarily on the slope of the field and whether the plough is a one-way or reversible plough. Four ploughing systems are commonly used:

Slope of field less than 2%:
1. Ploughing in lands with One-way ploughs:
2. Reversible ploughing with Reversible ploughs:

Slope of field between 2% and 12%:
3. One-way contour ploughing. For widely spaced contours part of the
fields may also be ploughed in lands, with One-way ploughs:

4. Reversible contour ploughing with Reversible ploughs:

In addition to the above four main ploughing systems another system, known as "corrective ploughing", is sometimes used to rectify the effects of poor ploughing procedures used in the past. These five systems will be described in detail in the following sections.

A.2.1. Ploughing in Lands

This system is recommended for use on a field larger than a land, see A.1.3, with a slope of less than 2% and which is to be ploughed with a one-way plough. The main components of the system are listed below:

- Main direction of ploughing:
  Generally along the longer side of the field, up to 150 m for animal drawn ploughs, and always along the longer side of the field for tractor drawn ploughs.

- Headlands:
  Normally required at both ends of the field, and along the side of the field, and they are ploughed after the lands have been ploughed.

- Lands:
  The criteria for when to divide a field into lands were given in A.1.3.

- Ploughing pattern:
  Adjacent lands are ploughed in different patterns. Lands being gathered are ploughed first, then the lands in between are ploughed by casting. This reduces the number of opening and finishing furrows that need to be made. The next time the lands are ploughed the alternative pattern is used on each land.

The steps to be taken in marking out and ploughing a field in this system are shown in Figure ___(@ AGRITEX TP2 p 5.12 to 5.16), and described below:

1. Place sticks at each corner of the field at a distance from the boundary equal to the width of the headland.
2. Divide the field into lands by placing sticks at each corner of the lands.
3. Mark the opening furrows. The first year these should be at the centre of the odd numbered lands and the second year these should be at the centre of the even numbered lands.
4. Turn a shallow furrow along the headland, following the sticks in a clockwise direction. The furrow, which should be roughly 5 cm deep, will ease the penetration of the ploughshare and enable it to reach its working depth quickly. Move and replace marking sticks. With a multi-bodied tractor drawn plough the plough is adjusted so that the furrow is ploughed with the rear body.
5. Open all opening furrows.
6. Plough the odd numbered lands, starting with the opening furrows and using the gathering pattern.
7. Plough the even numbered lands with the casting pattern. The opening furrow for this sequence will have been formed by the last run on the odd numbered lands. The following year the ploughing pattern is reversed.
8. After finishing all the lands the headlands are ploughed, at the same time as the parts of the field along the side of the lands. The headlands are "turned in" one year, i.e. ploughing is started at the ploughed side, and "turned out" the next year, i.e. ploughing is started at the boundary, so as to maintain the soil profile.

Figure ___(@ AGRITEX AP2 p 4.25 and 4.26, figs. 4.11 and 4.12) shows lands ploughed in the alternating gathering and casting pattern.

A.2.2. Reversible Ploughing

This system is used on fields with slopes of less than 2% that are to be ploughed with a
reversible plough. The main components of the system are listed below:

- **Main direction of ploughing:**
  Generally along the longer side of the field, up to 150 m for animal drawn ploughs, and always along the longer side of the field for tractor drawn ploughs.

- **Headlands:**
  Normally required at both ends of the field, and along the side of the field, and ploughed after the rest of the field has been ploughed.

- **Lands:**
  There is no need to plough in lands because the plough can throw soil to either side, and hence does not have to travel along the headlands. The headlands are only used for turning.

- **Ploughing pattern:**
  The soil is moved to one side on the whole field. The next time the field is ploughed, the soil is moved back by starting ploughing from the opposite side of the field.

The steps to be taken in marking out and ploughing a field in this system are simpler than those used in the one-way ploughing system. The headlands are marked out in the same way, but the field is not divided into lands. An opening furrow is made along one edge of the field and ploughing continues until the other end of the field is reached, as shown in Figure ___ (@ AGRITEX AP2 p 4.27, fig. 4.13). The following year ploughing should start at the opposite side of the field. The headlands are ploughed in the same manner as in the one-way ploughing system.

**A.2.3. Contour Ploughing**

Fields on slopes that are between 2 to 12% should be protected by conservation works. The broad range of land shapes between conservation contours is shown in Figure ___ (@ AGRITEX AP2 p 4.28, fig. 4.14).

Ploughing between contours should follow the contour lines as much as possible, to ensure that ploughing is across the slope and so increase infiltration and reduce runoff and soil erosion. This is easy to implement between parallel contours but more difficult when the contours are not parallel. In the latter case the field between the contours is an irregular shape and the best compromise should be chosen to ensure that the furrows generally lie across the slope, as indicated by the top and bottom contours, and that no portion is left unploughed. The way in which this is done using the one-way and reversible ploughs and for the different contour shapes is described in the following sections.

**A.2.3.1. One-way Contour Ploughing**

This system has been designed for fields with slopes between 2 and 12%, using a one-way plough. The main components of the system are listed below:

- **Main direction of ploughing:**
  Ploughing takes place between the contours, across the slope.

- **Headlands:**
  Turning takes place in the waterways and on the road crests. The headlands must not be ploughed because ploughing up and down the slope would lead to a high erosion potential.

- **Lands:**
  The criteria for when to divide a field into lands were given in A.1.3.

- **Ploughing pattern:**
  Gathering or casting patterns are used, but must be alternated each time the area is ploughed.

Where the distance between contours is substantially larger than a land then the area is divided into lands. The land nearest the upper and lower contours should then be ploughed
parallel to the contours and the ones in between in rectangular lands. Alternating gathering and casting patterns should be used on adjacent lands, and these in turn should be alternated from year to year. In the following examples it will be assumed that the area in between the contours is not larger than a land.

Where contours are parallel and straight, or parallel and curved, the distance between the contours is even throughout. The gathering pattern of ploughing is used in one year, with the opening furrow following the centre of the contours, and the casting pattern the following year. This is shown in Figure ___(@ AGRITEX AP2 p 4.30, figs. 4.15 and 4.16).

Where the contours are not parallel the furrows should follow the general slope as indicated by the contours as closely as possible, and no portion should be left unploughed. The land is ploughed such that no furrows start or end on the contours as this may divert water from the contours into the land. Again the whole land is ploughed in the casting pattern one year and in the gathering pattern the next. However, because of the irregular shape in between the contours, the marking out of the land is very different for the two patterns. Essentially, the land is divided roughly into two parts with part B being used as a headland for turning while part A is being ploughed. This is described below.

**Casting Ploughing Pattern:**

As shown in Figure ___(@ AGRITEX AP2 p 4.31, fig. 4.17), find the centre of the field by measuring across the space between the contours and mark the mid-points along the length of the field. This line will be about halfway across the slope within the contours, and ploughing must be planned to follow the higher contour on the one half and the lower contour on the lower half. A strip wide enough for turning must be left along the midline. As shown in Figure___(@ AGRITEX AP2 p 4.32, figs. 4.18 and 4.19) portion A is ploughed first, following the contours. Portion B is then ploughed so that the finishing furrow is at the centre X-X-X.

**Gathering Ploughing Pattern:**

As shown in Figure ____(@ AGRITEX AP2 p 4.33, fig. 4.20), measure the distance between the two contours at the narrowest part of the field. Divide this distance in half and then mark parallel strips following the contours as shown in the diagram as the B portions. Mark the parallel strip with sticks spaced at 10 m intervals, using a string between a person walking along the contour and a person placing the sticks to maintain a constant distance. For the line to be parallel it is important that the fixed length of string held between the two people is kept taut and that the string is kept at right angles to the contour bank. Once this has been completed plough a shallow furrow along this line as in marking out the headland. As shown in Figure ____(@ AGRITEX AP2 p 4.34, figs. 4.21 and 4.22) the A portion is ploughed first, stating at the centre, and turning on the B portions. The B portions are then ploughed, ending with a finishing furrow next to the contours.

### A.2.3.2. Reversible Contour Ploughing

This system has been designed for fields with slopes between 2 and 12%, using a reversible plough. The main components of the system are listed below:

- **Main direction of ploughing:**
  - Ploughing takes place between the contours, across the slope.
- **Headlands:**
  - As for one-way contour ploughing.
- **Lands:**
  - No lands required for the reversible plough.
- **Ploughing pattern:**
  - The soil is moved to one side on the whole field. Generally the next time the field is ploughed, the soil is moved back by starting ploughing from the opposite side of the
However, as the field is on a slope, soil is moved down the slope due to the effects of soil erosion. To compensate for this the soil is moved up the slope more frequently than the soil is moved down the slope, by starting to plough at the top of the slope more often than at the bottom of the slope. On steep slopes the soil may be moved up the slope three years in four or even more regularly. Care must be taken to ensure that the furrow immediately above the lower contour channel does not act as a small channel as this could lead to severe erosion.

Where the contours are parallel and straight, or parallel and curved, the field between the contours is ploughed by the reversible plough starting along a contour and continuing to the other contour, as shown in Figure ____(@ AGRITEX AP2 p 4.35, figs. 4.23 and 4.24). The soil is moved up or down the slope as discussed above.

Where the contours are not parallel the furrows should follow the general slope as indicated by the contours as closely as possible, and no portion should be left unploughed. The land is ploughed such that no furrows start or end in the contour channels as this may channel water from the contour channels into the land, which would lead to severe erosion. The whole area is generally ploughed by starting at the upper contour one year and at the lower contour the next. However, on steeper slopes the soil is thrown up the slope more often than the soil is thrown down the slope, as discussed above. The method used is described below.

The field should be marked and ploughed as shown in Figure ____(@ AGRITEX AP2 p 4.36, figs. 4.25 and 4.26). First, the centre of the shortest distance between the two contours is found, and from this a line is pegged following the bottom contour, to mark off section B. A shallow furrow is ploughed along the pegs, similar to that used to mark headlands, throwing the soil downhill. Ploughing is started from the top contour in section A down to the shallow furrow marking section B. Section B is then ploughed down to the edge of the contour channel.

To maintain the soil profile, the next time the field is ploughed the soil is thrown in the opposite direction, as shown in Figure ____(@ AGRITEX AP2 p 4.38, figs. 4.27 and 4.28). Section B is marked along the top contour and ploughing is started from the bottom contour in section A to the shallow furrow marking section B. Section B is then ploughed up to the top contour ridge.

A.2.4. Corrective Ploughing

Corrective ploughing systems are sometimes used to rectify the effects of poor ploughing procedures used in the past. The most common poor ploughing procedures usually involve use of the one-way plough and consist of many years of continuous gathering or continuous casting with no alternation between the two. This results in ridges and furrows being formed in the field that interfere with the desired runoff and drainage patterns. These lead to increased erosion and to reduced fertility, due to the erosion as well as excessive leaching in some areas. A further important consequence is the reduction in the area available for crop production. The resultant soil profiles are shown in Figure ____(@ AGRITEX Damscoop p 2.41, fig. 2.20).

Corrective ploughing is using a ploughing pattern to rectify the effects of the one that the farmer has been using continuously. For example, if the farmer has been continuously using the gathering pattern, then the casting pattern is used until the land is again level. However, this is a slow process, as it takes as long to rectify the problem as it took to create the problem in the first instance. The most desirable way to rectify the effects of poor ploughing is to use damscoops, landplanes and levellers as the land can be restored much quicker using these implements. Furthermore, these operations can be implemented outside of the growing season. However, they do require the availability of these implements as well as the availability of draught power.
Considerable effort may be required to restore the profile of poorly ploughed fields. Note that the aim is to get a uniform slope between contours and not necessarily to level the field to a horizontal plane. A dumpy level, staff and pegs is useful to determine the average original slope and to mark out where the cut and fill is required. It is important to clearly identify the proper conservation bank and furrow prior to pegging out the cut and fill areas. The soil may need to be loosened prior to using the soil levelling implements. Following the correction of the soil profile it is very important that the farmer should in future implement the correct ploughing systems.

A.2.5. Planning of Field Lay-out for the Ploughing System

At the start of Section A it was pointed out that one of the important steps made in preparation for the implementation of ploughing was the production of a sketch of the area. Figure ___(@ AGRITEX AP2 p 4.6. and 4.7., figs. 4.1. and (4.2) + p 4.39, fig. 4.29) shows an example of a typical rural field and the sketch of the field together with some of the standard notations that can be used.

An alternative to making a sketch on paper is to sketch in a sand tray, or to use sand in the field. A sand tray is also a very useful training aid. Using a model plough in a sand tray is much more realistic than a drawing on a blackboard or paper, and it is much faster than a ploughing demonstration in a field. A suitable sand tray is 2 m long, 1 m wide and 5 cm deep. The sand should be about 1.5 cm deep and should be sieved and mixed with a little oil so that it will hold its shape like damp soil. The model plough can be made in a workshop or can be a modified teaspoon, to give a cut of about 1.25 cm. The boundaries and contours should be drawn or built in realistic proportions to the plough.

Once the above has been done then the field should be marked out with sticks to show the headlands, lands and opening furrows. Following this a shallow furrow should be ploughed around the headland to mark it and to aid quick penetration of the plough. The field is then ready to be ploughed starting with the opening furrow.

5.3.4.2. Field Implementation of Secondary Tillage Operations

The main secondary tillage implements are cultivators, harrows and hoes, with rigid or sprung tines, or discs or various rotary soil engaging tools; rollers; levellers; and ridgers or Lister ploughs, and bed shaping implements. These implements were described in detail in Section 5.3.2, including their uses, operational characteristics and their adjustments. The depth of secondary tillage operations prior to planting, which are primarily determined by the requirements of the seedbed including the control of soil water and also of weeds, were discussed throughout Section 2 and particularly in Sections 2.1.2.5., 2.4.1.1., 2.4.2. and 2.4.5. This section will deal primarily with the required layout of the field for the implementation of secondary tillage operations prior to planting and the pattern of use of the implements within the field.

The field implementation of secondary tillage operations should be carried out in a well planned and systematic manner for the reasons given at the beginning of Section 5.3.4. For secondary tillage these reasons are primarily related to ensuring that the objectives of the tillage operation are achieved; minimising the recompaction of soil by minimising travelling over land that has already been tilled; observing soil and water conservation practices; and achieving high levels of field efficiency.

Most secondary tillage implements form small ridges and depressions, and on slopes greater than 2% these should be set across the slope to increase infiltration and reduce runoff and erosion. However, due to the smallness of the ridges and furrows ranges of operational
patterns are available. By contrast, the ridgers and bed-shapers are specifically designed to form large ridges and depressions. On slopes greater than 2% it is therefore very important that their layout and implementation are carried out according to set rules, otherwise they can result in increased rather than reduced erosion.

The selection of the various secondary tillage operational patterns, and the specific one used for the implementation of the ridging system, are described in detail in this section. This section is based closely on the AGRITEX Training Manual AETC, Animal Power 3, 1987, which should be referred to if a full training manual format is required, as well as Elwell and Norton (1988) for a detailed description of the ridging system.

A. Secondary Tillage Operation Patterns

Two main decisions need to be made when planning secondary tillage operation patterns:

- To identify the main direction of operation.
- To select a suitable operation pattern.

These two aspects are not independent of each other and the pattern of operation is largely determined by the main direction of operation. In addition to these two aspects tillage for seedbed preparation should follow the same pattern as that intended for planting, wherever possible. When this is done the field layout used for the tillage operations, and the direction of the small ridges left by the tillage operation, can be followed during planting.

A.1. Main Direction of Operation

On relatively flat fields, i.e. with a slope of less than 2%, the main direction of operation is as follows:

- Generally along the longest side of the field. This minimises the time spent turning and travelling on the headlands and thus maximises field efficiency.
- When the tillage operation has to be carried out twice at right angles, then the first operation is along the shorter side and the second operation is along the longer side. This is primarily because planting would be carried out along the longer side, to increase the field efficiency of planting and later crop maintenance operations. Planting could then follow the small ridges left by the last tillage operation.
- For very long fields, i.e. fields where the length is more than twice the width, and that are to be tilled twice at right angles, then the operation is carried out diagonally. This maximises field efficiency.

On sloping fields where the gradient is greater than 2% the main direction of the tillage operation is far more critical than on flat fields. This is particularly true of those operations that form large ridges and furrows, such as ridging and bed forming. For these latter operations it is very important that furrows in the field are always formed across the slope at a gentle gradient so that any water flowing in them flows at speeds below erosive levels. Furthermore, they should always drain smoothly into the waterway or bottom contour channel. They must be directed such that they cannot channel water from the bottom contour channel or waterway into the field, as this could lead to severe erosion. This requirement can be achieved by ensuring that ridges and furrows are parallel to the bottom contour when the contours are diverging towards the waterway, and parallel to the top contour when the contour ridges are converging towards the waterway. The validity of this rule can easily be seen by sketching the alternatives. This layout can be set up using a dumpy level and tape, but a simpler method is available known as the "string method". This method will be described in detail in the section on the field implementation of the ridging system.

Based on the above considerations, the main direction of operation on sloping fields where the gradient is greater than 2% is as follows:
- Generally across the slope to minimise water runoff and erosion.
- For fields with conservation ridges the following main directions are used for single operations:
  - Parallel contour ridges: Parallel to the conservation ridges.
  - Contour ridges converging towards the waterway: Parallel to top contour ridge.
  - Contour ridges diverging towards the waterway: Parallel to bottom contour ridge.
  - Irregular contour ridges: Parallel to the bottom contour when the contours are diverging towards the waterway, and parallel to the top contour when the contour ridges are converging towards the waterway.
- When the tillage operation has to be carried out twice at roughly right angles, then the direction will be dependent on whether the conservation contours are parallel or not:
  - Parallel contours: Diagonal zigzag pattern.
  - Irregular contours: Bottom contour followed first then top contour followed.

A.2. Operation Patterns

In order to maximise field efficiency and to minimise excessive compaction and overworking of the headlands, the following main secondary tillage operation patterns are used:
- To and fro operation pattern.
- Round and round operation pattern.
- Zigzag operation pattern.

The to and fro operation pattern is shown in Figure ___(@ AGRITEX AP3 p 1.20, fig. 1.8). The operation is started along one side of the field and continued by working back next to the previous line. This pattern is used when operating implements that cannot easily be lifted out of operation when travelling on the headlands, e.g. animal drawn harrows. For these implements this pattern ensures that the headlands are not overworked. A disadvantage of this pattern is the tight turn which has to be made in order to make the next run close to the previous run.

The round and round operation pattern is shown in Figure ___(@ AGRITEX AP3 p 1.21, fig. 1.9). Three types of pattern are shown. The first two involve turning on the headlands, and starting either in the centre of the field or at the edge of the field. These patterns can be used with implements that can be lifted out of operation when travelling on the headlands, to prevent overworking.

The third round and round operation pattern starts in the middle of the field, working outward without moving onto the headlands. With this pattern the length of the first run is determined by the width of the implement and the number of turns made to complete the field. For those implements that can be turned while they are still at operational depth, e.g. spike tooth harrows, this pattern can be completed without stopping. However, if animal draught power is being used then it will be necessary to stop for a few minutes occasionally to rest the animals. This pattern should only be used on flat fields and not on slopes greater than 2%, as some of the furrows would then be running up and down the slope.

The zigzag operation pattern is shown in Figure ___(@ AGRITEX AP3 p 1.22, fig. 1.10). A zigzag pattern is made, with each run parallel to the previous one and turning only at the headlands. When this pattern is used between contours it is very important that the contour ridges and furrows are not travelled over by the implement or the draught source, as this would damage the contours. The only exception to this is on broad-based contour ridges and furrows that are to be cultivated. The zigzag pattern is used when two operations at roughly right
angles to each other are required in order to obtain the required tilth. Two operations of the implement may be required to break down large clods or because only a light implement is available. Generally, carrying out the operations at right angles to each other produces much better results than two operations along the same main direction. This is particularly true for tined implements as a more uniform tilled depth is then achieved.

Based on the preceding discussions the various operation patterns for seedbed preparation and planting are shown in Table ___(@ AGRITEX AP3 p 1.23, table 1) and Table ___(@ AGRITEX AP3 p 1.24, table 2) respectively. The appropriate patterns for the type of field, the implement, and the main direction of operation can be selected from the table.

B. Field Implementation of the Tied-Ridge System

The ridge cultivation system was first developed in the humid temperate regions for poorly drained soils. Under these circumstances the raised ridge provides an area of well-drained soil in which the crop can be planted. In the tropical and subtropical regions, prone to high intensity rainstorms, the ridging system is primarily used as an important aid in reducing soil erosion on sloping fields. The ridges and furrows are carefully laid out on gentle gradients to reduce the speed of runoff on sloping fields and hence reduce erosion. In arid and semi-arid regions the system has been modified to include tying the ridges, or damming the furrows, to retain the water where it falls and so increase total infiltration, and thus reduce runoff and further reduce erosion losses. This was discussed in Section 2.2.1. The ties are constructed at one half to two thirds the height of the ridge, so that during heavy rain storms the ties overflow before the ridges do and the runoff is carried down the gentle gradient of the furrow. The tied-ridging system has been further modified to include a reduced tillage element to reduce the draught energy required to implement the system and to reduce the loss of soil organic matter. The attributes of the system are described in detail in Section 3.1.2.3 and it is covered in greater detail by Elwell and Norton (1988).

B.1. Selection of Lands for Ridging and Preliminary Preparations

The ridging system is seldom used on fields where the gradient is less than 2%. Crop ridges are normally set out on the same gradient as contour ridges, i.e. around 1 in 250, and should not exceed a gradient of 1 in 100. If the gradient of the ridge exceeds this latter value then the high speed of runoff in the furrow will start to lead to soil erosion. Due to this, care in the selection of lands for ridging is very important. The land surface must be sufficiently even to allow runoff in the furrows to flow without the maximum ridge gradient of 1 in 100 being exceeded. Lands badly incised by past erosion, or with uneven surfaces as a result of bad ploughing, must be levelled before they can be used safely. If this cannot be done due to the relatively high cost in terms of time and energy of levelling then they should not be cultivated using the ridging system. Levelling can be done by use of the dam scoop and land plane as described in Section 5.3.3. This is very important, as on uneven land the furrows will concentrate water at low points in the field. If the water flows over the ridges they will break, releasing the accumulated water at the low points and leading to much more severe erosion than if the field had not been ridged in the first instance.

Although the system can be installed on lands broken up by anthills and rock outcrops, there should not be too many of these obstacles otherwise the layout required for safe discharge becomes too difficult. Lands with lots of boulders on them are not suitable for ridging.

On fields with a slope of greater than 2% the ridge system should never be installed unless all the conservation works have been properly installed. These include contour ridges, waterways and storm drains as discussed in Section 4.2. Without these conservation works the crop ridges may be inundated with runoff from the neighbouring fields and as they are not designed to take large flow volumes they will be over-topped leading to severe erosion.
Furthermore, the runoff from the ridged field is concentrated into a limited area and unless they lead into a waterway that then spreads the water evenly over a large area they can also cause severe erosion. The conservation works should also be correctly laid out in relation to roads, paths, etc. Furthermore, existing contour ridges should be checked to make sure that they have been laid out at the correct gradients and spacing and are of the correct lengths. This is important as the crop ridges are set out using the contour ridges as a guide.

Other than the above there are no restrictions on implementing the ridge system on fields based on the steepness of their slope. However, it should be noted that greater care is needed in their layout, construction and maintenance as much more damage can be caused should the crop ridges be breached on steep lands. It should also be noted that cultivation on lands with slopes greater than 12% should generally not be practised unless they are terraced and fully protected with all the appropriate conservation works. This was discussed in Section 4.3 and references for more information on terracing were given in that section. Furthermore, cultivation on lands with slopes of greater than 12% is prohibited in many countries.

With the reduced-till tied-ridging system it is important that the ridges are not flattened by cattle trampling on them while grazing in the fields outside of the cropping season. Furthermore, contour ridges can also be damaged by the trampling action of cattle, particularly shortly after their construction and before they have become fully grassed over. For both of these cases it is important to keep cattle out of the fields due to the large amount of work involved in constructing and maintaining the ridges. For this reason it is strongly recommended that, wherever possible, the arable land is consolidated into large blocks and fenced or hedged off from the grazing area. Where this is not possible then it is important to remove crop residues from the field after harvest and to weed it effectively to discourage grazing animals from entering the field.

All ploughing and land preparation should be done in accordance with the procedures laid out in the preceding sections.

B.2. Setting Out the Crop Ridges

The art of correctly setting out the ridges is to decide on a gradient which is not so low that the crop ridges will be over-topped during storms and not so steep that the speed of water flow in the furrows is high enough to erode soil. It is recommended that crop ridge grades should not be flatter than 1 in 250 nor should they be steeper than 1 in 100, i.e. 1%. This means that on even lands where the contour ridges have been set out at their normal gradients of 1 in 250 to 1 in 150, that the crop ridges can be put in parallel to the contour ridges; but on uneven lands, the crop ridges should be steepened to 1 in 100.

Crop ridges should also always drain smoothly into the waterway or bottom contour channel. Care should be taken to turn down the ends of them to help them discharge into the grassed waterway. They must be directed such that they cannot channel water out of the bottom contour channel or waterway into the field, as this would lead to severe erosion. On even fields this requirement can be achieved by ensuring that ridges and furrows are parallel to the bottom contour when the contours are diverging towards the waterway, and parallel to the top contour when the contour ridges are converging towards the waterway. This was discussed in Section A.1 above and it is important that this rule is understood and remembered.

The crop ridges are set out by first of all setting out a "master ridge" between each pair of contour ridges according to the above criteria. All the other crop ridges are then set out parallel to the master ridge. This master ridge can be set up by using a dumpy level and tape, but the "string method" is quicker and easier.

B.2.1. The String Method
The string method is a simple technique requiring only three people, a supply of pegs and a ball of string. The method of setting out the master ridge is shown in Figure ___(@AGRITEX AP3 p.1.17 and 1.18, figs. 1.6a and 1.6b) and described below:

- **Start at the highest point of the contour and work towards the discharge end**, i.e. start at the crest and end at the waterway. One person must be in the channel of the top contour holding a ball of string and one person in the channel of the lower contour holding the other end of the string. A firm tension should be kept on the string.
- The master ridge is started at an arbitrary distance of 1 m below the top contour. A marker, such as a piece of material is tied in the string about 1 m below the top contour ridge. It is very important that the marker cannot move on the string. The third person then puts a peg in the soil under the marker.
- The team walks along the contour channel for an agreed distance, usually 10 to 15 paces, and the third person puts a peg in the soil under the marker each time they stop.
- When the contours converge, i.e. get closer together towards the waterway, the string becomes slack as the team moves down the contours. The person walking in the upper contour should then hold firmly to the same place on the string, while the person on the lower contour maintains the tension by reeling in the slack.
- When the contours diverge, i.e. become further apart towards the waterway, the string becomes too short as the team moves down the contours. The person walking in the lower contour should then hold firmly to the same place on the string, while the person on the upper contour lets out some string.
- When the agreed number of paces has been covered, the team stops and the third person puts a peg into the ground below the marker.
- It is very important to keep the string at right angles between the master ridge and the contour to which it is being made parallel. This should be controlled by the person who is holding fast to the string, i.e. the one who is not letting out or reeling in the string. When the team stops, after having taken the agreed number of paces, the person who has been holding fast must be the one to correct the line of the string so that it is at right angles to the contour on which that person is standing.
- This procedure is continued until there is a continuous line of pegs laid out from the crest down to the waterway. Some adjustments can be made to give smooth curves and to turn down the end next to the waterway.
- The line of pegs marks out the master furrow and its gradient is the same as that of the contour ridges.

The basic rule of the string line method, when moving from the crest to the waterway, is that the person on the upper contour must only let string out, and the person on the lower contour must only reel string in.

When marking out a number of contours it is possible to alternate the above method with one moving from waterway to crest, in order to save time. This method involves the person on the bottom contour staying where they are, while the one on the upper contour leapfrogs down to the contour below their teammate. The person on the new bottom contour then reels the string in until the marker is 1 m above the new bottom contour. The team then walks up the contours pegging the next master furrow. The basic rule given in the previous paragraph is then reversed, as the team is now moving in the reverse direction. Notice that, because of the leap-frogging, this method means that when the string gets tight it is always the same person as before who lets out the string; and when the string gets slack, it is always the same person who reels in. This method is described in greater detail by Elwell and Norton (1988), but if it is considered that using both methods will lead to confusion then it is better to only train staff to use the former method.

Above the top contour and below the bottom contour, where there are no "partner" contours to work with, the crop ridges are set out parallel to the sole contour ridge.

**B.2.2. Steepening the Master Ridge**
As discussed previously, land with an uneven surface should generally be levelled before crop ridges are laid out. However, levelling land is expensive in terms of time and energy and in some instances only partial levelling may be possible or financially desirable. The gradient of the crop ridges can be steepened up to a maximum gradient of 1% to compensate for the unevenness of the land.

The gradient of the master ridge is steepened when the land surface is uneven to the extent that the crop ridges would be over-topped if they were put in at the same gradient as the contour ridges. Elwell and Norton (1988) describe a method whereby the master ridge is steepened to the desired gradient by moving the peg at the waterway end a calculated distance down the slope and adjusting all the other pegs proportionally to give the entire length of the master ridge a uniform gradient, as shown in Figure ___(Elwell and Norton (1988) p 22, fig. 5).

The distance that the peg at the waterway end has to be moved is given by the following equation:

$$H = \frac{100 \times L(1/X - 1/G)}{S}$$

Where:
- $H$: The horizontal distance that the peg at the waterway end has to be moved.
- $L$: The length of the master ridge in metres.
- $1/X$: The gradient to which the master ridge is to be steepened.
- $1/G$: The original gradient of the master ridge, which is equal to the gradient of the contour ridges.
- $S$: The percent slope of the land.

The distances that the intermediate pegs have to be moved can most easily be calculated as multiples of the distance that the first peg down from the crest has to be moved, as shown in Figure ___(Elwell and Norton (1988) p 22, fig. 5), and as given by the following equation:

$$h = Y \times \frac{H}{L}$$

Where:
- $h$: The distance that the first peg down from the crest has to be moved. It must be emphasised that the peg at the crest is not moved. The second peg down from the crest is moved a distance of $2 \times h$.
- $Y$: The distance between the pegs.

When the peg at the waterway end is moved down the required distance it may be found that it is then positioned below the lower contour bank. This does not affect the method and the contour bank should be crossed and the peg put in position. However, when all the intermediate pegs have also been adjusted, the new master ridge should end at the point where it reaches the lower contour channel. All the pegs below the lower contour bank should be pulled out before the master furrow is made.

On uneven land it may be found that the crop ridges regularly break at fixed points even though the ridges have been put in at the maximum grade of 1%. If this happens then either further land levelling is necessary, or otherwise an extra waterway may be needed at one or more of the points where the ridges break.

B.3. Dealing with Obstructions When Ridging

The best method of dealing with obstructions to the continuous run of the ridges, such
as anthills or rock outcrops, is to stop the ridge just before the depression which often occurs at the foot of such obstructions. If the depression does not exist then one must be made so that the furrows can drain smoothly into the depression. The depression then becomes a small grassed waterway leading the runoff down to the contour ridge below, as shown in Figure ___(Elwell and Norton (1988) p 24, fig. 6). Low spots at the sites of old erosion channels can be dealt with in the same way, but they should be gently graded and grassed over to turn them into safe waterways. The direction of the crop ridges must be maintained, so even if an obstruction is met in the field the direction of the crop ridges must be set out as if the obstruction did not exist.

With regard to the general layout of the contour ridges for the crop ridge system of cultivation, it should be noted that a greater proportion of the land is available for cultivation when the contour channel is brought as close as possible to the lower side of the obstruction. If the obstruction is an anthill the most satisfactory long-term solution is to remove it.

B.4. Size and Spacing of the Crop Ridges and Ties

The standard size and spacing of the crop ridges and ties should be determined by the main extension organisation for each country or region. The minimum size and maximum spacing of the ridges to avoid over-topping during rain storms is determined by the volume of runoff that the furrows are expected to be able to carry. This is primarily determined by the following factors:

- The maximum rainfall intensity for which the system is designed. This is combined with the worst-case assumption that a rainstorm of maximum intensity occurs when the soil is already saturated and infiltration is at a minimum, so that maximum runoff occurs.
- The maximum length of ridge, which together with the maximum amount of runoff, determines the maximum flow rate at the end of the ridge, per unit spacing of the ridges. The length of the ridge is equal to the length of the contour bank from crest to waterway and maximum lengths of these are specified according to region and soil type, etc.
- The maximum depth of flow within the furrow during maximum runoff will occur under the following conditions; the slope of ridge is at a minimum; the soil coarseness in the furrow is at a maximum; and the height of the ties is at a maximum. A less than uniform gradient on uneven lands, which will lead to a greater depth of flow at the low points, should also be taken into account.

For those countries where the ridge system of cultivation has been used for a long period of time the sizes and spacing of the ridges is likely to have been determined by trial and error. However, the sizes and spacings should be checked for the rainfall conditions pertaining in each region, by calculations based on the above criteria. This is to ensure that the dimensions are a suitable balance between the need to prevent overtopping and the need to minimise the energy input required for their implementation.

The recommended height and spacing of ridges in Zimbabwe is shown in Figure ___(Elwell and Norton (1988) p 25, fig. 7). The crop ridges should not be less than 250 mm high when just built and not less than 200 mm when they have become consolidated. A spacing of 900 mm between the crop ridges is usually adequate for most cropping situations and, since the angle of repose of loose earth is about 30 to 33 degrees, these dimensions allow the width of the top of the ridge to be 200 mm which is sufficient in which to plant two rows of close grown crops, such as groundnuts or soybeans. Although the spacings between ridges can be widened out to 1 m if preferred, wider spacings than 1 m are not recommended in Zimbabwe, as there is then a danger of the ridges overtopping because of the fewer channels carrying the storm flow.

Ridges are tied, or the furrows dammed, in order to retain the water on the soil surface where it falls, so as to increase the length of time that infiltration can occur. This both aids
water conservation and also minimises runoff and hence erosion. However, it is very important that during heavy storms the water in the furrows can overflow the ties and flow down the gentle gradient of the furrow. If the ties are so high that water overtops the ridges severe erosion will occur. To prevent this the ties are built at one half to two thirds the height of the unconsolidated ridge. The ties are generally spaced at about 700 to 1000 mm intervals along the furrows, but the spacing is also determined by the amount of loose soil available in the furrow for tie construction. Excess water, accumulating on the crest path or road, must be prevented from entering the top end of the furrows, otherwise the ridges may be overtopped. For this reason the upper end of each furrow must be blocked off by an extra-large tie. During very wet periods the ties can be broken to improve drainage and prevent waterlogging.

B.5. Construction of the Crop Ridges and Ties

The master ridge is constructed first and then all other ridges are built parallel to it. The crop ridges should be constructed and tied, or the existing ridges re-ridged and tied, before the start of the first rains, in order to make most use of their water conserving and erosion reducing characteristics. The operations can be timed to advantage to coincide with the need to control winter weeds so that the construction and weeding can be done together.

Ridges are normally constructed using tractor or animal drawn ridger bodies, which were described in Section 5.3.2.7. A wide range of ridger bodies is available and it is important that generally those with the lowest draught energy requirements are chosen. To comply with this, one of the requirements is that the forward or backward projection of the ridger body should be roughly the same as that of the furrow cross-section that it is expected to construct. If this is not the case then soil is moved unnecessarily, leading to excessive draught power requirements. The ridger body should also be able to be adjusted so that it can be used for weeding the growing crop, by just cutting under the surface of the sides and bottom of the furrow, without digging into the ridge and pruning the crop plants' roots. It should be noted that some of the animal drawn ridger bodies which have low adjustable wing tips are paradoxically called high wing ridgers, and these low wing tips can cut the crop plants' roots during weeding operations.

The animal drawn plough can also be used to construct the ridges and to maintain them if animal drawn ridger bodies are not available. However, two runs are then required to be made for the construction of each ridge, which is costly both in terms of time and energy. Ridges are also commonly made with hoes in many countries, however the demands on time and labour are very high.

The ties are constructed using tractor or animal drawn tie-makers or by using the hand hoe. These were described in Sections 5.3.2.7 and 5.3.2.8 respectively. The animal drawn tie-makers are very simple implements and as they require very little draught power they can be drawn by one animal.

5.4. PLANTING OPERATIONS AND IMPLEMENTS

Crop planting operations may involve the random scattering or dropping of seeds on the field surface, the placing of seeds or tubers in the soil in rows at a specific depth, or setting plants into the field. This section will concentrate on the planting of seeds and will deal only briefly with the planting of tubers and with transplanting at the end of the section.

The agronomic aspects relating to planting requirements were covered in Section 2.4.1.1. Planting operations and implements are described in training manual format in AGRITEX AP3 (1987), covering manual techniques and animal drawn implements, and AGRITEX TP4 (1988), covering tractor drawn implements. The principles of planting machinery are also covered by Kepner et al (1978) and these publications have been used
extensively in this section.

5.4.1. **Planting Methods and Requirements**

Seeds may be planted according to any of the following main methods:

1. **Broadcasting:** Random scattering of seeds over the surface of the field.
2. **Drill seeding:** Random dropping and covering of seeds in furrows to give definite rows.
3. **Precision planting:** Accurate placing of single seeds at about equal intervals in rows.
4. **Hill dropping:** Placing groups of seeds at about equal intervals in rows.

Two further categories of planting are known as solid planting and row-crop planting. When seeds are scattered, or planted in rows that are insufficiently wide apart to allow machinery to operate between them during subsequent operations, e.g. less than roughly 40 cm, the result is known as solid planting and is generally implemented by one of the first two methods. When the rows are sufficiently wide apart to allow machinery to operate between them, e.g. greater than roughly 40 cm, it is known as row-crop planting and any method of planting other than broadcasting may be used.

The planting methods to be used for each crop type should be recommended by the main agronomic extension organisation in each country. This information should be based on previous research and experience within the country, which should have included collaboration with the local tillage and mechanisation organisations. The same planting methods are generally used for each crop type for the various agro-ecological zones even though the tillage systems used may vary markedly.

The main planting requirements to be considered when planning and implementing planting operations are listed below:

- Required crop plant population.
- Method of planting.
- Spacing requirements.
- Depth of planting.
- Time of planting.

The agronomic details concerning the above requirements were covered in Section 2.4.1.1. and these should be referred to again. Only those aspects relating to the field implementation of the planting operations will be covered in this section.

The main agronomic extension organisation in each country should recommend the range of values for the planting requirements, for each of the specific agro-ecological zones within the country and with adjustments specified for a number of factors. These will then need to be selected for compatibility with the farmer's specific circumstances and available equipment.

As Kepner et al (1978) point out, the primary objective of any planting operation is to establish an optimum plant population at optimum plant spacing, with the ultimate goal being to obtain the maximum net return per hectare. Population and spacing requirements are influenced by such factors as the kind of crop, type of soil, the fertility level of the soil, the amount of moisture available, and the effect of plant and row spacing upon the cost and convenience of operations such as thinning, weed control, cultivation, and harvesting. For many crops there is a fairly narrow range of plant populations that will give the maximum yield under a particular set of conditions.

Once the optimum plant population has been determined and the method of planting selected for the specific crop, the next main consideration is plant spacing. For broadcast crops
the mean plant spacing is determined by the plant population, but for row crop planting the row and in-row spacings have to be selected. The selection of row and in-row spacing is based on a compromise between acceptable access to light, moisture and nutrients, and the mechanisation requirements. As discussed in Section 2.4.1.1 most crops can tolerate moderate variations in uniformity of in-row plant spacing without seriously affecting yield, providing the average population density is within the optimum range. The relationship between plant population, row spacing and in-row spacing is given with sufficient accuracy by the following equation:

\[ P = \frac{10000}{r \times s} \]

Where:  
- \( P \) - Plant population per ha.  
- \( r \) - Row spacing (m).  
- \( s \) - In-row spacing (m).

When using the above equation to calculate the seed spacing required to achieve the desired plant population it is important to remember to increase the seeding rate by the amount of losses expected between planting and emergence. These losses are made up of two components, viz. the difference between the number of seeds planted and the number that germinate, and the difference between the number of germinated seeds and the number that emerge. These figures will vary between crops and the varieties of those crops and the standard figures to be used should be given by the seed distributors and extension organisations. The required seeding rate is calculated as follows:

\[ S = \frac{P}{((100 - G)/100 \times (100 - E)/100)} \]

Where:  
- \( S \) - Seeding rate, per ha.  
- \( P \) - Plant population per ha.  
- \( G \) - Germination rate, %.  
- \( E \) - Emergence rate, %.

To calculate the modified in-row spacing for the seeds the plant population is replaced by the seeding rate in the first equation. The row spacing is not modified. The above equations apply primarily to precision planting. For drill seeding there is no need to calculate the in-row spacing. For hill dropping the in-row spacing between the groups of seeds can be calculated by dividing the plant population by the desired number of plants in each group, and then modifying for germination and emergence rates, as above.

The factors controlling the depth of planting and the time of planting were discussed in Section 2.4.1.1. It is worthwhile restating that generally the planting depth of a seed is ten times its diameter, as shown in Figure ____ (AGRITEX AP3 p 4.5, fig. 4.2.). However, this depth needs to be adjusted to allow for soil moisture conditions and expected rainfall patterns, as discussed in Section 2.4.1.1. If the crop is planted after the first rains it may be desirable to soak the seed for 12 to 18 hours before planting in order to reduce the germination time, which can be critical if the rains are not regular at planting time. However, soaking can reduce the effect of seed dressing and also makes the seed more vulnerable to damage by the mechanical metering devices in planters.

5.4.2. Manual Planting and the Use of Hand Implements

All of the main planting methods described above can be implemented using manual planting methods. These include broadcasting seeds by hand and manual planting behind mouldboard or chisel ploughs, hoes, planting sticks and jab planters, as shown in Figure ____(@ AGRITEX AP3 p 3.19, fig. 3.2 + p 4.18, fig. 4.5 + p 4.24, fig. 4.10)
The main advantages of manual planting are that costly, specialised equipment is not required. With care, reasonably accurate planting can be achieved in terms of both spacing and depth control. The main disadvantages of manual planting are the high labour and time requirements. These disadvantages can result in high labour or opportunity costs, and in the lack of timeliness of the completion of planting which in those regions with a limited growing season can result in a loss of yield. As with all planting one of the most important factors is to ensure that the required seed population is achieved. It is therefore crucial that the methods used are planned and calibrated to achieve this goal.

When applying fertilizer or broadcasting seed the use of an apron bag suspended from the shoulders, rather than a bucket or sack, allows both arms to be used, which can speed up the operation. Fertilizer should be incorporated into the soil as soon as possible, prior to planting. Broadcasting is conducted by following the steps below:

- Select a swath, or width, suited to the operator and the type of seed.
- Walk steadily at a set length of stride along parallel lines.
- Evenly throw equal handfuls of seed at each step or alternate step depending on whether the container allows one or both arms to be used.
- Walk parallel to the previous swath edge or previous line of footprints for the subsequent runs, aiming to re-fill the container after a set number of runs to save time and energy.
- Once the seed has been broadcast it is incorporated into the soil by the use of hand rakes or animal drawn implements such as the spike tooth harrow.

For broadcasting, the required seeding rate is generally given in terms of kg/ha for each variety. If it is not, then this can be calculated from the plant population requirement after factoring it up for expected germination and emergence losses. The planting procedure can be tested by broadcasting across a set swath along a 10 metre distance to check that the selected swath and length of pace give the required application rate. The amount to be applied over the test area can be calculated by multiplying the required seeding rate, in terms of kg/ha, by the test area, i.e. 10 m times the swath width, measured in metres, and divided by 10000 to convert it to hectares.

The planting methods other than broadcasting involve placing the seed in parallel rows at a specific depth within the soil. This involves four steps, i.e. marking the rows, making a hole to the required depth, placing the seed, and covering the seed and firming the soil.

It is important for subsequent mechanised operations that rows are equally spaced and parallel. When animal drawn implements are to be used a row marker can be used to mark out the next furrow line. The row marker consists of an arm, which can be pivoted to either side of the tillage implement or seeder, and an adjustable follower to mark out the next furrow. When only hand implements are to be used then parallel lines should be marked out on the soil to be followed by the planters. The farmer can easily make a simple wooden marking rake with the distance between the tines equal to the row spacing. The implement is used by running the end tine of the marker in the last furrow left by the previous run. For crops with a wide in-row seed spacing a second marking rake, with the distance between the tines equal to the in-row spacing, can be used at 90 degrees to the first rows to mark out the planting holes.

If fertilizer is to be applied, and if it is not to be broadcast but banded, then it is generally applied at the same time as planting. One person should then be responsible for planting and another for fertilizer application as the rates of application are different. It is generally important, especially with the concentrated fertilizers, that the fertilizer and seed do not come into contact otherwise the seed may be burnt. This can be achieved by making a deeper hole, placing the fertilizer in the hole and covering it with soil prior to placing the seed at the required depth. For most crops the seed should be roughly 5 cm deeper and 5 cm to one side of the seed. Fertilizer application will be dealt with in greater depth in the next main section.
Drill seeding can be implemented by hand by dribbling seed into the open furrow left behind a chisel plough. The seed is generally covered by means of an animal drawn spike tooth harrow or by dragging a spade along the furrow. If fertilizer is to be applied this should be carried out before the seed placement with some soil scraped into the furrow prior to the seed being dribbled in. The original depth of the furrow and the amount of soil scraped in should be such that the seed is placed at the correct depth and at the required distance above the fertilizer. If a mouldboard plough is to be used the fertilizer can be placed 5 cm to one side of the seed. The seed is automatically covered by the next run of the mouldboard plough. The application rate of the seed is calibrated in the same manner as for the broadcasting procedure described above, with the row spacing replacing the swath width.

Precision planting and hill dropping can also be carried out behind a chisel or mouldboard plough, or by using a hand hoe, planting sticks or seed jabbers. When planting behind ploughs a similar procedure to that described above is used. However, a distance marker stick, or wheel of set circumference, or some similar device, is required to gauge the seed spacing. These distance markers can also be used when planting with a hand hoe. Alternatively the hoe can be marked such that the distance between the blade and mark is equal to the seed spacing and the mark is held over the last hole when marking the next. The hoe is also used to cover up the fertilizer, if used, and the seed, and the soil is firmed by stepping on the area where the seed has been planted. Planting sticks and seed jabbers can also be used to plant seed and they are particularly useful within reduced tillage systems planting into crop residues. However, with these implements the fertilizer has to be applied separately.

Animal drawn mouldboard and chisel ploughs can fairly easily be modified to become planters or planter/fertilizers with the operators taking the place of the mechanical metering devices. A funnel at waist height, into which the seed is dropped, is connected to a tube that ends at the required depth behind the soil engaging tool. The calibration of the application rate for drill seeding or the metering of the distance between seeds for precision planting is the same as that described above. Alternatively, for precision planting, a wheel whose circumference is equal to the seed spacing or multiples thereof can be used. Visual markers are attached to the wheel, or otherwise a clapper to produce sounds can be tripped by the markers, to indicate the seed spacing. A chain pulled behind the implement can be used to cover the seed.

5.4.3. Animal and Tractor Drawn Planters

All of the main planting methods described at the beginning of this section can be implemented using tractor drawn planters. Animal drawn planters are most commonly designed for precision planting and occasionally for drill seeding. Broadcasting with animal drawn planters can be carried out using full width seed spreaders. The main types of planters are named after the planting methods that they are used to implement. A range of these planters are shown in Figures ___(@ AGRITEX TP4 p 6.9, fig. 6.4, + p 7.3, fig. 7.1 + p 8.4, fig. 8.1, + AP3 p 3.25 fig. 3.5)

Kepner et al (1978) point out that seed planters, with the exception of broadcasters, are required to perform the following mechanical functions:

- Open the seed furrow to the required depth.
- Meter the seed.
- Deposit the seed in the furrow in an acceptable pattern.
- Cover the seed and compact the soil around the seed to the proper degree for the type of crop involved.

Furthermore, the planters should not damage the seed enough to appreciably affect
germination. The seed should be placed in the soil in such a manner that all the factors affecting germination and emergence will be as favourable as possible. Since timeliness is important in the majority of planting operations, it is desirable that planters are able to perform these functions at fairly high planting speeds.

The primary function of a broadcaster is to meter the seed and distribute it with reasonable uniformity over a given width of land, or swath. Covering is a separate operation or is omitted entirely under some conditions.

The main advantages of animal and tractor drawn planters over manual methods of planting are their much higher work rates, and hence improved timeliness; their lower labour requirements; and their generally greater accuracy of planting, which results in improved germination and emergence. The main disadvantages are their higher capital and running costs and the financial risks they expose the farmers to. The gradation of these factors between manual, animal and tractor power sources was discussed in Section 5.2.

There is generally little fundamental difference between animal drawn and tractor drawn planters, with the exception of the tractor p.t.o. driven pneumatic planters. Due to their basic similarity no major distinction will be made between them in the following discussions. However, it should be noted that animal drawn planters generally consist of single rather than multiple planter units, that they are simpler, and their quality of production is also generally much lower than that of tractor drawn planters. Due to the frequent poor quality of animal drawn planters, or the lack of availability of suitably sized metering plates for locally or currently available seeds, planting by hand is often a more accurate and cost beneficial means of planting than using animal drawn planters. Due to the relatively high cost of animal drawn planters for resource poor farmers, extension organisations should accurately assess locally available animal drawn planters and their parts before promoting their use to farmers. It is also very important that information regarding problems encountered with planters, and all implements for that matter, should be communicated to dealers and manufacturers and the issues raised should be followed up.

Different crops and different planting conditions require different types of planters, or different types of components on the planters, and the following will be discussed further; devices for metering seeds; furrow openers; covering devices; types of planters and row-crop planter arrangements. The adjustment of the components or the way in which they affect planting accuracy will also be discussed where appropriate.

5.4.3.1. Devices for Metering Seeds

There are two main types of devices for metering seeds, viz. bulk-flow seed metering devices and single seed metering devices. The former are used for broadcasting and drill seeding and the latter for precision planting and, with outsize seed cells, for hill dropping.

Bulk-Flow Seed Metering Devices

The bulk-flow seed metering devices, used for broadcasting and drill seeding, deliver a fairly continuous flow of seeds and there are four main types, shown in Figure (Kepner 1978, p 219, figs 10.10 to 10.12 + AGRITEX TP4 p 7.4. fig. 7.2) and described below:

- Fluted-wheel seed meters:
  A force-feed meter used mainly on grain and grass drills and to a limited extent on row-crop planters. They are suitable for use with only relatively small seeds. The seeding rate is usually controlled by either moving the wheel axially to change the length of flutes exposed to the seed in the feed cup, or by changing the speed ratio between the ground wheels and the feed shaft. The size of the feed slide opening and the base flap opening are determined by the size of the
seeds, with larger seeds requiring larger openings. These settings also affect the seeding rate and it is important that the manufacturers settings are adhered to.

- **Internal double-run seed meters:**
  A force-feed meter used for similar purposes to the fluted-wheel type, but suitable for large seeds as well as small seeds. Only one side is used at any one time, the side selected depending on the seed size. The seeding rate is controlled by changing the speed ratio between the ground wheels and the feed shaft.

- **Cup-feed seed meters:**
  A force-feed meter used for similar purposes to the above and suitable for large and small seeds. Each cup on the outer edge of the disc picks up a few seeds that are dropped into the seed tube leading to the furrow opener. The seeding rate is controlled by changing the size of the cups or by changing the speed ratio between the ground wheels and the feed shaft.

- **Stationary-opening seed meters:**
  A simple meter that is not force-fed and is frequently used on broadcast seeders, for planting vegetable seeds and for some other row-crops. The seeding rate is controlled by adjusting the size of the opening. Agitators are used to prevent the seeds from bridging over the opening and to maintain an even flow rate.

The essential difference between the force-feed types and the stationary-opening type are that with the former the seeding rate is directly proportional to the forward speed, i.e. the number of seeds metered per unit distance is independent of the forward speed. Because of this, force-feed seed meters are more accurate and less prone to operator error once correctly adjusted.

The manufacturer should have calibrated the seed drills and have provided charts to provide the correct setting of the gearbox, base flap and feed slide, according to the required seeding rate and seed size. However, seed sizes vary and a calibration test should be carried out prior to planting. This is usually most easily done with the planter stationary and the wheels being rotated by hand. The following equation and procedure is used for force-feed meters:

\[
T = S \times Td \times W / 10000
\]

Where:
- \( T \) - Amount of seed to be sown in test area, kg.
- \( S \) - Seeding rate, kg/ha.
- \( Td \) - Test distance, in m, usually 100 m.
- \( W \) - Working width of planter, m.

The number of revolutions of the wheel is calculated by dividing the test distance by the circumference of the wheel, i.e. \( 3.14 \times \) wheel diameter in metres. The test is conducted by filling the seed hoppers; raising the drill and securing it in place; placing a collection tray under the metering devices; rotating the drive wheel several times to allow the seed to fill the metering devices and then emptying the collection tray; marking a spot on the drive wheel and rotating it through the calculated number of revolutions to equal the test distance, and also rotating the wheel at roughly the speed that it would be operating in the field; and then weighing the seed in the collection tray. If the collected seed weighs significantly more or less than the amount, \( T \), calculated above, then set the gearbox to a lower or higher number respectively, and then repeat the test. This procedure can be used for a single row planter by using the row width as the working width in the above equation.

For some single unit force-feed metering devices it may be more convenient to calibrate the application rate in terms of grams per metre forward distance as given by the following equation:
\[ A = S \times \frac{r}{10} \]

Where:
- \( A \) - Application rate per metering device, g/m.
- \( S \) - Seeding rate, kg/ha.
- \( r \) - Row spacing, m.

The derivation of this equation is similar to the previous equation and is based on determining the total distance that has to be covered to plant the whole hectare. This is calculated by dividing the hectare by the row spacing. The rest of the equation is based on converting the relevant units. Calibrating a planter using this equation is similar to the procedure given above.

When calibrating stationary-opening metering devices it is the time that the seed is dribbled out of the opening that is of importance, rather than the number of revolutions of the wheel or the distance travelled. The amount of seed that is to be sown in the test area, i.e. 100 m times working width, is calculated in the same manner as above. However, instead of rotating the wheel a set number of times, the length of time that it would take the planter to cover the test distance is measured or calculated. The test seed sample is then collected for this length of time. The drive wheels should be rotated throughout this period as the agitator affects the flow rate and it prevents bridging of the seed over the outlet.

**Single Seed Metering Devices**

Single seed metering devices usually have cells on a moving member or an arrangement to pick up single seeds and lift them out of the seed mass. They are used for precision planting, and for hill dropping when a seed cell size is selected which is large enough to contain the required number of seeds to be dropped in a group. There are five main types, shown in Figure (Kepner 1978, p 214, figs. 10.2, 10.3, 10.5, 10.6, 10.7, 10.9 + AGRITEX TP4 p 8.7), and described below:

- **Cell-plate seed meters:**
  - These consist primarily of circular plates, rotated about their centre, with equidistant seed-cells on their periphery, with the seed-cell being slightly larger than the thickness and width of the seed. The seeds in the hopper above the rotating plate slot into the cells and are then dropped through the cell into the seed tube as the seed-cell rotates above the seed tube. The seed spacing is determined by the number of holes in the seed-plate and the gearing between the drive wheel and the seed-plate. These seed meters are divided into horizontal and inclined-plate types. In both types the seed mass pressing down on the seed plate automatically ejects those seeds not correctly aligned in the cells, thus allowing another seed to slot in correctly. In the horizontal-plate meters the unloading of excess seeds is achieved with a spring-loaded cut off. In the inclined-plate seed meters the seeds are picked up at the bottom of the incline and rotated upwards out of the seed mass. A stationary brush is sometimes used for more positive unloading, but no cut off device is used. This results in the seeds being handled more gently, which results in less damage to seeds and thus improved germination performance. The proportion of the seed-plate immersed in the seed mass is controlled by the feed-slide opening. A spring-loaded knockout pawl is commonly used in both types to eject the seeds into the seed tube.
  - The cells in the plates may be either on the edge, known as edge-cells, or fully contained within the plate and these may be round or oval. Edge-cells are well suited for planting relatively large, flat seeds like maize. The cells are tapered with the diameter of the top of the cell being slightly smaller than that of the bottom, to facilitate ease of ejection of the seed and to reduce the likelihood of the seed jamming in the cell. The plates and the surrounding ring, which forms
one side of the cell, are accurately machined to provide uniform cell sizes for precision metering and to reduce damage to the seeds. A large selection of plates is necessary to meet the requirements of the many types and sizes of seeds and spacings.

- For accurate metering the following points should be noted:
  - The seed to be planted should be graded to ensure that the seed are of uniform size and shape. Large seeds will jam in the cells and block them and small seeds will result in more than one seed being planted at a time. Both can also result in damage to the seed from protruding seeds hitting the cut off.
  - The diameter of the cells should be 10% larger than the largest dimension of the seed.
  - The width of the plate should be equal to the average diameter of the seeds. A recessed base plate may be used to accommodate broad seeds.
  - The linear speed of the seed cell should be relatively low to achieve good cell fill and to reduce damage to seeds. To achieve this it is better to increase the number of holes in the seed-plate and to correspondingly reduce the rotational speed of the seed-plate, to achieve the desired seed spacing.

- **Vertical-rotor seed meters:**
  - These consist primarily of a cylinder, rotated around its axis, with the seed-cells formed into the surface of the cylinder like cups. They are often used for the precision seeding of vegetables and sugar beets. The position of the seed hopper relative to the rotor determines whether the action of the rotor is similar to that of the horizontal or inclined-plate seed meters described above. When the seed-hopper is directly above the rotor a seed cut off device is required. If the hopper delivers the seed-mass behind the rotor, then its action is more similar to the inclined-plate seed meter and only a brush is required for more positive unloading, which results in less damage to the seeds. The seeds are ejected by a stationary ejector operating in a machined groove. The points listed above regarding accurate seed metering for cell-type seed meters also apply to vertical-rotor seed meters.

- **Belt-type seed meters:**
  - These meters operate on a similar principle to the plate-type seed meters, but with a continuous belt replacing the plate. Seed from the hopper enters the chamber laterally, above the part of the belt running along the bottom of the device, where it is maintained at a controlled level allowing seeds to slot into the seed-cells. A counter-rotating seed repeller pushes back excess seeds. Seeds in the cells are conveyed over the base and discharged from the belt beneath the seed repeller wheel. Lack of a positive unloading device causes some variability in seed spacing. Seed spacing is determined by the number of holes in the belt, i.e. the seed spacing on the belt, and the gearing between the ground drive and the belt drive. The points listed above regarding accurate seed metering for cell-type seed meters also apply to belt-type seed meters.

- **Finger pick-up seed meter:**
  - In these meters, spring-loaded, cam-operated fingers on radial arms rotate in contact with a stationary disc. The fingers grip one or more seeds against the disc as they pass through the seed reservoir. All but one seed is released as each finger passes over two small indents near the top of the stationary disc. As the finger continues to rotate, it passes over an opening in the disc and kicks the seed through this into a large cell in an adjacent, rotating seed wheel. The seed wheel discharges the individual seeds into the furrow, minimising the distance that the seed falls and thus improving accuracy.
  - Seed spacing is adjusted by altering the gearing between the drive wheel and the metering device.
The main advantage of these seed meters is that they can tolerate a much greater variation in seed size than the previously described seed meters, whilst minimizing damage to seeds and maintaining high levels of accuracy. This contrasts with the other systems described which require a large selection of plates, rotors, or belts, to cater for the different seed sizes and spacings.

- **Pneumatic seed meters:**
  - A number of different devices have been developed and they use either a positive or negative pressure, and may use either a drum rotor for planting multiple crop rows, or a disc rotor for single crop rows. In the drums there is one circumferential row of perforated seed pockets for each planter row. The rotors are ground-driven so that seed spacing is independent of forward travel speed. The positive or negative air pressure is generally developed by a p.t.o.-driven fan providing a differential pressure across the disc or drum of around 4 kPa. The differential pressure over the perforated seed pockets picks up the seed from the seed-mass and holds the seed against the perforations. This pressure is generally cut off by wheels at some point during the revolution on the opposite side to which the seed is being held, which releases the seed into the seed-tube. In the positive pressure systems the seeds are usually fed to the inside of the rotor, whereas in the negative pressure systems the seeds are usually picked up on the outside of the rotor. By contrast, the principle of one particular positive pressure system depends on several seeds being fed into cone-shaped cells on the outside of a rotating disc and a jet of air blowing all except one seed out of the cone. Generally, vacuum-pickup devices can perform effectively even with small, irregular-shaped seeds like lettuce, but they are more sensitive to dust and dirt than positive pressure systems.
  - Seed spacing is adjusted primarily by altering the gearing between the drive wheel and the rotor. Different rotors are used for different kinds of seeds.
  - The main advantage of pneumatic seed meters is that they minimise damage to seeds, maintain high levels of accuracy and can tolerate a large variation in seed size.

The calibration of precision planters is straightforward. All precision planters are driven by a ground wheel, usually the press-wheel. The number of seeds dropped per unit distance, and hence the seed spacing, is the main parameter of interest. This can be calculated from the number of times a seed cell passes the seed tube per revolution of the drive wheel. The latter can be calculated from the gearing ratio between the drive wheel and the metering device and the number of seed cells or equivalent in the metering device, or otherwise simply observed. The circumference of the ground wheel, and hence the distance travelled per revolution, is measured using a tape measure, or calculated from its diameter. The planter is then adjusted to provide the required seed spacing.

The calibration of the planter can be checked statically or in the field. The static test involves rotating the drive wheel a set number of turns at roughly the operational speed, counting the seeds dropped, and determining whether these correspond to the required seeding rate in terms of numbers per meter or the required seed spacing. The field test involves operating the planter in the field over a set distance, at the operational speed, and counting the number of seeds dropped. If there is a significant difference between the numbers dropped and the numbers expected, then the gearing and the number of holes in the seed plates, etc., should be checked and recalibrated. The advantage of the field test over the static test is that it is easier to check for multiples of seeds dropped at the same time, or for misses. If their frequency of occurrence is excessive this may indicate that the holes of the seed plate are too large or too small respectively, or that there is some other problem with the metering device. In both cases at least 30 seeds should be dropped, the metering mechanism should be full of seeds before the test starts, and the test should be conducted at roughly standard operational speed. The latter requirement is important because on some metering devices the percentage of cell-fill varies with the rotational speed of the metering device.
The seed-metering device should be as low and close to the furrow as possible so that the accuracy of the seed-metering device is not undermined. A long seed tube allows some seeds to drop smoothly down it while others may bounce from side to side, taking longer to fall to the furrow, and hence altering the seed spacing.

Standard testing procedures for planters are given by the International Organisation for Standardisation in their publication ISO 7256/1. These tests are meant for use by agricultural machinery testing centres and not by farmers. Although the tests specify specialised equipment, any testing centre could improvise to satisfy most of the testing requirements. The jargon used in the description of the tests will require the testers to be familiar with testing procedures, otherwise additional advice will be required. Manufacturers should be in a position to provide copies of test results carried out by a recognised testing institution. These tests should generally be carried out for the commonly used planters in the country with the commonly used seed, and before any specific planters are recommended for use by the extension organisations. It is very important that extension organisations ensure that planter manufacturers and distributors are kept up to date with the latest seed sizes and seed spacing requirements.

5.4.3.2. Furrow Openers

All planting methods other than broadcasting require that the seed is placed at a specific depth below the surface, which generally requires the use of a furrow opener. The optimum planting depth varies widely with different crops and is influenced by soil moisture conditions and anticipated rainfall patterns, soil temperature, time of year, etc. Some seeds are more sensitive to variations in planting depth than others. In addition to the planting requirements, the amount of crop residues on the surface and the soil conditions also determine the type of furrow opener to be used.

A range of fixed and rotating type furrow openers are shown in Figure ___(@ Kepner 1978, p 221, fig. 10.13.), and the conditions for which they are most suitable are described below:

- **Full or curved runner:**
  
  A simple device that works well at medium depth in mellow soil free of crop residues and weeds. It is suitable for average conditions encountered by maize and cotton planters in conventional tillage systems. Horizontal plate-type depth controls may be attached to the runner for soft soils.

- **Stub runner:**
  
  Sometimes used on maize planters in rough soils or those with low levels of crop residues or weeds.

- **Hoe-type openers with spring trips:**
  
  These are suitable for soils with lots of stones or roots in them. They, or similar shovel type openers, may also be used for deep placement of seeds if the soil is free of crop residues.

- **Disc-type openers (rotating):**
  
  These are suitable for use when penetration through crop residues or into hard ground is required. In wet, sticky soils they are more satisfactory than fixed openers because they can be kept reasonably clean with scrapers.

  - **Single-disc openers:**
    
    These are more effective than the double-disc opener in penetrating and cutting through crop residues. Single-disc openers with mouldboard attachments are used for furrow planting of grain, the drilled surface being left as a series of furrows and ridges.

  - **Double-disc openers:**
These are particularly well adapted to medium or shallow seeding of row crops that are critical in regard to planting depth, because the depth can be controlled accurately with removable depth bands.

- **Disc-type openers with coulters:**
  Most zero-till drills use coulters to cut through heavy residues without destroying or covering them, and to open a slot immediately ahead of a double-disc opener. The coulters are usually operated about 10 mm shallower than the disc openers.

### 5.4.3.3. Covering Devices

To achieve optimum germination and emergence results, planters should be designed to pack the soil below the seed level, press the seeds into the compacted soil, and cover the seeds with loose soil. Increasing seed/soil contact below and around the seed improves capillary continuity between the lower moist soil layers and the upper layers in which the seed is planted, and between the seed and soil immediately surrounding it. Leaving the soil immediately above the seed row loose minimises crusting and promotes easy emergence.

Some seeds are more sensitive to the above factors than others, and this also varies with moisture conditions. For example, simple drag chains, which merely cover the seeds with loose soil, are satisfactory for grain drills under most conditions where there is ample moisture. In loose, sandy soils and where moisture is a limiting factor, the use of narrow press-wheels operating behind the opener to compact the soil below the seed tend to give increased stands and yields. The use of a narrow rubber-tired press-wheel to press the seed into the furrow bottom, prior to the seeds being covered, sometimes improves emergence, especially with cotton.

Packing the soil below seed level is often carried out as a separate operation with rollers. Sometimes it is achieved by using a press-wheel behind the openers or alternatively by the action of the seed tube opening running behind the furrow opener and slightly packing soil that has fallen back into the furrow. It is very important that the seed tubes are shaped such that they cannot be blocked up with moist soil. A narrow rubber-tired press-wheel running in the furrow directly behind the seed tube can be used to press the seed into the bottom of the furrow before the seed is covered. This wheel can also be used to pack the soil below the seed level and press the seed into the compacted soil at the same time.

Many types of covering devices are used, including, drag chains, drag bars, scraper blades, steel press-wheels, rubber-covered or zero-pressure pneumatic press-wheels, disk hillers, and various combinations of these units. Figure ___ (@ Kepner 1978, p 222, fig. 10.14) shows some of the types of press-wheels employed on row-crop planters, and their uses are described below:

- **Open-centre, concave, steel press-wheels:**
  These pack the soil around the seeds leaving the soil immediately above the seed fairly loose. Commonly used for maize and other large-seed crops.

- **Tires with narrow centre ribs:**
  These press down firmly around the seed and have given good results in sugar beets. A drag chain behind the press-wheel fills the remaining groove.

- **Zero-pressure pneumatic press-wheels:**
  Used extensively for vegetables and some other crops. Their continual flexing tends to make them self-cleaning.

- **Narrow rubber-tired seed packer wheels:**
  Used in the furrow directly behind the seed tube to press the seed into the bottom of the furrow before the seed is covered.
The main types of planters can be divided into broadcasters, drill seeders and precision planters, based on the planting methods that they are used to implement. A brief description of these is given below:

- **Broadcasters:**
  - Machine broadcasting of seed is more accurate and rapid than broadcasting by hand. Broadcasters are generally of the single static-opening type metering device with a centrifugal distribution device, or of the drop-type with spaced static-opening metering devices spread over the full width of operation. Only the latter type is available for animal draught use. Both of these machine types can also be used for applying granular fertilizer. If broadcasted seed is to be covered this is done as a separate operation, usually with a spike-tooth harrow.

- **Drill seeders:**
  - This method has almost replaced the broadcasting method because of the greater uniformity of seed distribution and the more uniform seeding depth. Drill seeders use both static opening and bulk-flow metering devices, but usually the latter as they are more accurate and are independent of the speed of operation. The metering devices are driven by end-wheels or the press-wheels. The maximum depth of the furrow openers is controlled in gangs, usually through adjustments to the lift arrangement. Each opener, however, is held down by spring pressure and can rise independently to pass over obstacles.
  - Drill seeders can be divided into the following categories:
    - Surface drills: Used on well prepared seedbeds with low levels of residues, not exceeding 500 kg/ha, and where the depth to the moist soil is not great. These usually use single or double disc openers with row spacings of 150 to 200 mm, and they place seeds at depths less than 70 mm.
    - Furrow drills: Used to plant into the bottom of a furrow so that the seed can be placed into moist soil, which is below a deep layer of dry soil. Also used when a furrow is required to provide protection to young seedlings from wind and to roughen the surface so that wind erosion is minimised. Furrow drills with a vertical clearance of about 460 mm can easily pass through 3000 to 4000 kg/ha of dry cereal residues. They usually use shovel or hoe-type openers for zero or very low residue levels, and single-disc openers for higher residue levels. Seed row spacings of 180 to 400 mm are available, with the openers and seed tubes staggered in two or three rows for residue clearance.
    - Zero-till drills: These are specialised drills that have been developed to seed through heavy residues without destroying or covering them. They usually use coulters to cut through the residue immediately ahead of a double-disc opener.
  - The fertilizer-grain combination drills have divided hoppers, the front section being for seed and the rear section for fertilizer. The fertilizer may be deposited through the same tubes with the seed or through separate passages behind the seed tubes. Some types of fertilizers should never be allowed to come into contact with the seed. Drill seeders can be used for row-crop planting by blocking off appropriately spaced seed and fertilizer outlets.

- **Precision planters:**
  - These planters are used for precision planting and for hill dropping. Single seed metering devices are used, with large seed-cells used for hill dropping. However, for hill dropping there is likely to be considerable scattering of seeds, particularly at high forward speeds, unless a rotary valve or transfer wheel is used. This wheel accumulates the desired number of seeds for a hill as they are discharged from the metering plate and discharges them close to the furrow openers.
bottom at a low velocity relative to the ground. The metering devices are usually driven by the press-wheels.

- Precision planters are adaptable to a wide variety of crops and tillage systems and many different combinations of furrow openers, metering units and covering devices are used. Depth is controlled by either the press-wheel, gauge wheel, shoes on the runner-openers, or depth bands on double disc-openers. If a thick layer of dry soil overlies a moist seed zone, the coulter can be replaced with a scraper or disc-furrower to allow seed placement into the moist soil. Tool-bar mounted unit planters are popular because of their great versatility in regard to row spacings and the type of seed they can plant. Planters may be the mounted or pull type and can plant 2 to 12 rows. Unit planters are attached to the tool-bar or planter frame with parallel-link mechanisms to ensure that the furrow openers and press-wheel maintain their relative positions to the horizontal. On mounted planters the use of planter weight transfer kits is desirable. These consist of springs that transfer weight to the planter, ensuring a positive drive from the press-wheels to the metering device at all times.

- Fertilizer attachments are commonly used to band fertilizer below and to the side of the seeds.

5.4.4. **Planting Tubers and Transplanting**

On small-scale farms tubers are usually planted by hand, but mechanised planters are available. For example, automatic potato planters have vertical, rotating picker wheels with devices that either pierce or grip individual seed pieces and then drop them into the furrow.

Some kind of crops, including tobacco, cabbage, sweet potatoes, and tomatoes, may be propagated in special beds and then transplanted in the field. If large areas are to be planted then mechanical aids are usually employed. As Kepner et al (1978) point out, the essential components of simple transplanting machines are a furrow opener, provision for carrying a supply of plants, low seats for operators who place plants directly in the furrow, and press-wheels or press-plates to cover the roots and firm the soil around them. A water supply tank is usually provided for intermittent or continuous application. Plants are spaced in response to a mechanical clicking device or other appropriate signal. Runner-type furrow openers are usually used.

More complex transplanting machines employ mechanical transfer devices that are handfed but automatically place the plants in the row. These must be carefully designed to ensure that the plants will not be damaged. Both simple and complex transplanting machines must also be designed to preclude any possibility of injury to the operators.

5.5. **FERTILIZING OPERATIONS AND IMPLEMENTS**

Fertilizers are applied to the soil to increase the available supply of plant nutrients, and thus promote greater yields or better crop quality. Crop fertilizing operations may involve broadcasting the fertilizer on the surface, with or without incorporation into the soil, banding fertilizer on the surface or at depth, and the placement of pockets of fertilizer near the seed or plant. This section will concentrate on the field implementation of fertilizing operations.

The agronomic aspects relating to fertilizer requirements were covered in Section 2.4.1.3 and the principles of fertilizing equipment are covered by Kepner et al (1978). Fertilizing operations and implements are described in training manual format in AGRITEX AP3 (1987), covering manual techniques and animal drawn implements, and AGRITEX TP4 (1988), covering tractor drawn implements. These publications have been used extensively in this
5.5.1. **Fertilizing Methods and Requirements**

As discussed in Section 2.4.1.3 there are 16 essential elements necessary for normal crop growth, and if any of these are missing growth will be retarded or the crop may die. The primary nutrients are nitrogen, phosphorous and potassium. Calcium, magnesium and sulphur are secondary nutrients that are generally required in smaller amounts than the primary elements, depending on the crop species, soil conditions and climate. Fertilizers can be divided into two main categories, namely, organic fertilizers, which provide nutrients and organic matter, and inorganic fertilizers, which provide nutrients. Both affect soil pH, with organic fertilizers providing more of a buffering action, and inorganic fertilizers, and especially nitrogenous fertilizers, capable of substantially reducing pH over a period of time.

Organic fertilizers are generally in the form of dry farmyard manure or compost, wet slurry, or green manures. The basic methods of spreading or incorporating them are described below:

- **Farmyard manure and compost:**
  - On small-scale farms, distribution is dependent on available transport, labour and the amount involved. It is usually applied before ploughing or ridging so that after spreading the manure can be incorporated in the soil to a depth of at least 15 cm. The desired application rates are large, from 15 to 30 tonnes per hectare. If only small quantities are available then it is preferable to distribute them at the desired rates on fields to be used for the most important crops, or to band them near to the seed or growing plant. On medium and large-scale farms tractor drawn manure spreaders are commonly used.

- **Wet slurry:**
  - Rotary tractor-drawn and p.t.o. driven spreaders are commonly used.

- **Green manures:**
  - Leguminous crops such as sunhemp, beans and cowpeas are commonly used. They are ploughed under when they are at the flowering stage and still green.

Inorganic fertilizers may be in the form of liquids, granules, or powders. Dry inorganic fertilizers may be applied in association with most cultivation operations, and their main application methods are described below:

- **Broadcasted before ploughing, or placed at ploughing depth by a distributer on the plough that drops fertilizer in each furrow.**
- **Deep placement with chisel-type cultivators.**
- **Broadcasted and mixed into the soil, or drilled into the soil, after ploughing and before planting.**
- **Banded during the planting operation.**
- **Banded side-dressing applications on growing row crops, generally during a cultivation operation, or broadcasted top dressing on solid-planted crops.**
- **Drilled into established pastures and other sods with special equipment.**

Application rates of 225 to 560 kg/ha per treatment are common, but may be as high as 1100 kg/ha. For high application rates for row crops, a portion of the total amount is often broadcast and incorporated prior to planting.

Liquid inorganic fertilizers can be divided into high-, low- or non-pressure liquids depending on their vapour pressures. High- and low-pressure liquid fertilizers lose nutrients by evaporation, and hence must be stored in pressurised containers and also be injected into the soil in deep furrows and quickly covered. Non-pressure fertilizer liquids may be applied by any of the methods employed for dry fertilizers. For example, anhydrous ammonia (NH₃) is classified as a high-pressure liquid fertilizer (vapour pressure of 860 kPa at 24 deg. C and
1720 kPa at 46 deg. C), and is commonly the least expensive source of nitrogen. Aqua ammonia (NH₄OH) is classified as a low-pressure liquid fertilizer (vapour pressure seldom exceeds 170 kPa). Mixed fertilizers and solutions not containing ammonia are non-pressure liquid fertilizers.

Liquid and dry inorganic fertilizers are sometimes applied through irrigation water. Special injection systems have been developed for metering and introducing low-pressure or non-pressure liquids and dry materials into irrigation streams or pipelines. One advantage of these systems is that mineral deficiencies can be quickly overcome that would otherwise seriously impair growth or yield. Excessive concentrations of some chemicals will injure leaves or fruit, and low concentration spray applications may need to be repeated at frequent intervals.

Materials such as lime and gypsum are not fertilizers but are frequently used to improve the chemical (pH) or physical condition of the soil. They are usually applied before planting but can be applied to a crop at any stage without injury. Application rates are generally much higher than for commercial fertilizers, ranging from 1000 kg/ha to several times this amount.

Many factors influence the successful use of fertilizers, and the following five main requirements need to be determined:

- Type of fertilizers required.
- Application rate, kg/ha.
- Position of placement of fertilizer relative to seeds or plants in terms of distance and depth.
- Timing of initial application and top dressings.
- Equipment to be used and calibrations to be made.

The type of fertilizers required and the amounts required will depend on the soil type and condition, the climate, the tillage system used, the crop to be grown, the yield required as determined by a cost benefit analysis based on the production factors of the fertilizers, etc. The agronomic extension services should provide this information in easily calculable form. A soil analysis to determine the condition of the soil should also be carried out as discussed in Section 2.4.1.3.

As described above several alternative placement positions are available for selection, and these partly depend on the type of fertilizer being applied. Because movement of most fertilizers in the soil is very limited, especially of phosphorous, proper placement in relation to the seeds or plant roots is important for maximum response and the most efficient utilisation of nutrients. Banding of the fertilizer near the seeds at the time of planting, rather than broadcasting, favours early stimulation of the seedlings and results in more effective utilisation of the plant nutrients by the crop. The latter is because the soil ties up some of the nutrients making them unavailable to the plant, and with banding there is less contact between the soil and the fertilizer as compared to broadcasting. Furthermore, the banded fertilizer is placed in the root zone of the seedlings, giving them greater access to the nutrients than weeds growing between the rows. However, excessive concentrations of soluble nutrients in contact with seeds or small roots may injure the initial roots or even impair germination. Kepner et al (1978) points out that best trial results for initial applications with most row crops have been obtained when the bands were 25 to 75 mm below the level of the seed and 40 to 100 mm laterally from the row on one or both sides, depending on the crop and conditions. A mean of 50 mm below and 50 mm to one side is often selected for most crops. An important reason for banding below the seed zone in arid areas is that dry fertilizer only releases nutrients when it is moist, and these conditions are likely to occur for longer periods in the lower soil layers. The deeper placement of fertilizers also encourages deeper rooting, allowing the plant to extract moisture from a greater depth and volume of soil.

Because nitrogenous fertilizers are easily leached, they are not all applied before or
during planting and are also applied during crop growth as top dressings. This is done at critical stages of crop development before fruiting. Resource-poor farmers may only apply the fertilizer as a top dressing and its application will depend on the rainfall pattern over the growing season.

Fertilizers applied as top dressing, or row-crop side dressings, are of most immediate benefit when placed in moist soil within the root zone, but excessive mechanical destruction of the root system must be avoided. Side dressings are usually applied in conjunction with a cultivation operation. The fertilizer is generally dropped in furrows opened by regular cultivator shovels but it can be placed at other locations or depths with separate, narrow-shovel openers or chisels.

5.5.2. Manual Fertilizing and the Use of Hand Implements

All of the main fertilizing methods described above can be implemented using manual fertilizing methods. These include broadcasting fertilizer by hand, banding by hand, the use of hoes and mouldboard or chisel ploughs, as shown in Figure ____ (@ AGRITEX AP3 p 3.19 fig. 3.2 + p 4.18, fig. 4.5 + p 4.24, fig. 4.10)

Manual fertilizing methods will not be covered in much detail here as the methods used are almost identical to those used for manual planting and these were described in detail in the previous section. The main advantages and disadvantages of manual fertilizing are similar to those for manual planting.

The methods and calibrations used for broadcasting and banding fertilizer are identical to those used for broadcasting and banding seed. The application rate for banding fertilizer is calculated in the same manner as for the broadcasting procedure described previously, but with the row spacing replacing the swath width.

5.5.3. Animal and Tractor Drawn Fertilizers

All of the main fertilizing methods described at the beginning of this section can be implemented using tractor drawn fertilizers. Animal drawn implements are most commonly planter/fertilizer combinations designed for precision planting and fertilizing and for drill seeding and fertilizing. A range of these fertilizers are shown in Figure ____(@ AGRITEX TP4 p 2.3, fig. 2.1, + p 3.3, fig. 3.1 + AP3 p 3.25 fig. 3.5).

Kepner et al (1978) point out that the basic performance requirement for a fertilizer distributor is uniformity of distribution over a wide range of conditions. For drop-type units or band placement, uniformity is determined primarily by the performance of the metering devices. With centrifugal broadcasters, both metering and lateral spread must be considered. The following design parameters are desirable:

- The metering device should ideally have a positive dispensing action, rather than be of the stationery-opening type. It is desirable that the discharge rate should be proportional to the forward speed of the implement so that the application rate per hectare will be independent of speed.
- The rate should be adjustable in small increments and should have a definite relation to a suitable reference scale provided on the unit.
- The design should be such that there are no appreciable cyclic variations in discharge rate.
- The discharge rate should cover a wide range of drillabilities. Where drillability is defined as the ease with which the fertilizer flows.
- The discharge rate should be independent of the depth of the fertilizer in the hopper and of reasonable inclinations of the hopper.
- Hoppers should be designed to be easily tipped or removed and the metering devices
easily dismantled, to facilitate cleaning, as fertilizers are often corrosive. Corrosion-resistant materials should be used where feasible.

A wide range of metering devices are used in fertilizer distributors, including star-wheels, augers, vertical-rotor edge-cells, rotating-bottom and gate, stationary-opening types, etc., described by Kepner et al (1978) and shown in Figure ___(@ Kepner p 264 to 267, figs. 12.1 to 12.7). The discharge rates of most of these metering devices are altered by means of changing the setting of a gate or opening, or of altering the gearing between the rotor speed and the forward speed, etc. Those metering devices that have positive dispensing actions are ground driven so that the discharge rate is proportional to the forward speed of the implement. Agitators are used, also ground driven, to prevent bridging of the fertilizer over the metering devices.

The calibration of positive dispensing action and stationary-opening metering devices is identical to that of planters using bulk-flow metering devices as described in Section 5.4.3.1. The calibration of the former type is based on a test distance whereas that of the latter is based on the time taken to cover that test distance.

The affect on the discharge rate of the type and condition of the fertilizer and the operating conditions depends on the extent to which the specific system relies on gravity flow. Auger feeds, belt feeds, and cell-type units are essentially positive-displacement devices. Star-wheel feed systems have a positive action on the material carried between the fingers, but depend partly on gravity for the flow through the gate opening above the top of the wheel. Stationary-opening arrangements depend largely on gravity. Kepner et al (1978) report a series of tests that determined that the drillability of a fertilizer is inversely proportional to its angle of repose, and where this is greater than about 55 deg. they cannot be metered satisfactorily with most types of equipment. The discharge rates of all systems are affected by the specific gravity of the material.

With spinning disc and oscillating spout spreaders the lateral distribution of the fertilizer is such that some overlap of the swaths is required to produce an even distribution of fertilizer over the field, as shown in Figure ___(@ AGRITEX TP3 p 2.12, fig. 2.5). The amount of overlap required should be specified by the manufacturer. This can also be checked in a test station by collecting the amount distributed onto corrugated iron sheets and comparing the amounts collected in the same lengths of the corrugations.

Godwin (1990) describes two systems of fertilizing systems for use in areas of low rainfall, and these two systems are shown in Figure ___(@ Godwin 1990, p 105 fig. 4.18 and fig. 4.19), and described below:

- In the USA paired-row system, the deep precision placement of fertilizer between the paired-rows encourages deeper rooting and provides a supply of nutrients where available moisture is likely to be present for longer periods.
- The system developed by the International Centre for Agricultural Research in Dry Areas (ICARDA) in Aleppo, Syria, is similar to the former and has been developed for smaller scale equipment and for a high field efficiency. The system is installed in a one-pass operation, with the ridges and furrows formed with lister-type shovels, the fertilizer being placed in the bottom of the furrows, the seeds then broadcast, and a bar pulled behind which rolls the soil from the ridge tops and covers the fertilizer and seed. The seeds are thereby concentrated at different depths in a zone above the fertilizer band. This system should lead to good fertilizer efficiency and sowing the seeds at different depths spreads the risk for plant emergence in areas of low rainfall with unreliable rainfall patterns.
6. CARE AND MAINTENANCE OF EQUIPMENT AND ADHERENCE OF SAFETY PRECAUTIONS

In order to be able to implement the various tillage and cultivation operations in a timely, efficient and cost effective manner it is essential that farm equipment is properly cared for and maintained. This involves operating the equipment in a deliberate and careful manner to minimise the possibility of breakages, and to service machinery and equipment on a daily, weekly and longer fixed period basis. In order to be able to do this it is important that operators are trained in the correct selection, adjustment and operation of farm machinery and equipment, as well as its daily and weekly servicing. It is also important that the lubricants, spare parts and servicing facilities and schedules are planned for, purchased and stocked prior to them being needed. The order of complexity of these requirements increases sharply as the power sources used change from manual to animal to motorised.

One of the most important resources that farmers have is their own health and that of labourers on their farm. Because of this, and particularly because so many farm machines and implements are dangerous when operated incorrectly, it is essential that appropriate safety precautions are observed at all times. Most of these precautions are based on common sense, but experience has shown that serious and costly accidents will occur unless farmers and supporting organisations take steps to continually remind and train operators in the importance of safety.

This publication will only deal with the basic principles of the maintenance and safety aspects of tillage implements and some other cultivation implements. The operator's handbook, which should be produced by reputable manufacturers or dealers for all motors and complex implements, should always be closely followed. This is particularly important, as the conditions of operation are likely to affect any warrantee arrangements that may exist. The following publications are useful sources of reference; the AGRITEX training manuals TP1 to TP5 and AP1 TO AP4; Lovegrove (1968).

6.1. CARE AND MAINTENANCE OF TILLAGE AND CULTIVATION EQUIPMENT

Cultivation equipment should be operated with care and properly maintained for the following main reasons:
- To prevent delays at the start of cultivation operations, by ensuring that all required equipment is available and in optimum working condition when the operation is planned to start.
- To minimise the time, and hence cost, required to complete the operation. Good maintenance will reduce the time needed to be spent on equipment adjustments, and also reduce the likelihood of failures occurring during its use.
- To minimise the energy required to operate the implement. For example a rusty mouldboard plough or one with a blunt share has a higher draught requirement than a polished plough with a sharp share. Thus the fatigue of draught animals can be reduced and hence the time that they can work lengthened. Likewise, fuel costs can be reduced for motor-powered implements.
- To prolong the service life of the equipment and thus save on overall costs.
- To minimise the chance of injury to the operator.

The main rule for operating equipment with care is to do so in such a manner that the forces operating on the implement are minimised. This is particularly true of forces exerted on the implement that are not in the direction that the implement is designed to withstand. The following examples are given:
- The soil engaging components of tractor drawn implements should be fully lifted out of contact with the soil when turning on headlands or when reversing.
- Great care should be taken not to turn too sharply so that undue forces are exerted on
the implements. In particular it is important the tractor wheels do not come into contact with the drawbar or the lower links of the three-point linkage system.

- Check-chains should always be used and correctly adjusted when an implement is attached to the three-point linkage system. During operation neither of the two check-chains should be taught except for occasional periods. If the implement is pulling to one side then it should be readjusted to pull in a straight line. The inside lugs of the tractor wheels should be checked at the end of a day's operation to ensure that they have not been damaged by coming into contact with the three-point linkage system.

- For transport the check-chains should be tightened so that minimal lateral movement of the implement is allowed. The top link should be shortened to increase the height of the end of the implement off the ground to prevent impact when going over bumps.

- Implements should be operated within the range of their design speeds, and especially not faster than their maximum design speeds. Speeds should be reduced over rough surfaces. Wherever possible conservation works should not be crossed and if this is done then speeds should be kept low. Transport speeds, especially over rough surfaces with mounted implements, should be kept as low as practicable.

- When successive tillage operations follow the same operation pattern then the tractor and implements are subjected to a less rough surface than when they are operating at right angles to the previous operation. Only a few tillage operations require that the latter condition is tolerated.

- Fields should be well stumped and rocks removed from them prior to tillage to minimise damage to tillage implements and to increase field efficiency. Farm roads should be kept in as good condition as possible.

The main principles and aspects of maintenance will be described below for tillage implements, planters and fertilizers. The operation and maintenance of tractors will only be covered very briefly. Following this a brief outline of programmes to promote good maintenance will be given.

Tractors are costly and complex and it is important to set up a well designed framework for their operation and maintenance. Operators should be well trained and incentives built in to their wage structures to properly maintain and operate the tractors, so that they are used in a cost efficient manner with the minimum of breakdowns. On large farms or when tractors are used in a co-operative system then it is highly desirable that one operator is permanently assigned to an individual tractor. If this is done then it is easier to build up an ethos of responsibility of the operators for their equipment, as it is easier to assign responsibility to individuals for the good or poor performance of particular tractors and other pieces of equipment.

For tractors, daily, weekly and longer period checks and services should be carried out. A schedule of these checks and services should be drawn up and displayed in the sheds in which the tractors are stored overnight or at the locations where they are checked and serviced. The tractor operators should note the tractor hours, fuel and lubricants added, duties carried out etc., and sign off that the checks have been carried out each day. This information should also be used for farm management analysis. Examples of these schedules of checks and maintenance are given in AGRITEX TP1 (1986). Whereas tractor operators should be responsible for the daily and weekly checks and maintenance, only qualified mechanics should be allowed to carry out the more complex longer period services, and these are generally carried out off the farm at service stations.

It is beyond the scope of this publication to deal with the complex servicing and maintenance requirements of tractors and other motorised farm machinery. However, any extension workers responsible for advising farmers using tractors should be aware of the factors involved, because of their high cost and complexity, and for this a basic tractor maintenance and operation course manual such as AGRITEX TP1 (1986), should be consulted.
Tractor and animal drawn equipment should also be checked and serviced on a daily, weekly and longer period basis. In these cases the periodic maintenance is usually at the end of a period of use, or at the end of the season, prior to the implement being stored for a time. When an implement is being taken out of storage it should also be serviced prior to use. It is very important that operators are trained how to operate the implements correctly and how to maintain them.

The following maintenance procedures are given as general guidelines for tillage, planting and fertilizing implements. Reference should always be made to operator's manuals for instructions about a specific implement.

1. Tillage Implements:

The following tools and items are generally required: Brush (wire plus nylon/straw), cloths, spanners (correctly sized) and screw drivers, oil-can or oil and paintbrush, grease-gun for bearings on disc ploughs, paint, etc. A stock of spare parts required for daily and weekly maintenance and likely breakdowns should be acquired prior to the season starting. Generalised procedures for daily and seasonal maintenance are given first followed by additional items for specific implements.

1.a. Daily maintenance while in use:
   - Scrape or brush off soil without further removal of paint, by using non-wire brush on painted parts. Generally do not wash down as this encourages rust. If the implement is not to be used within 5 days then bright soil engaging parts, and nuts and bolts, should be treated with a light coating of waste oil or rust inhibitors to prevent rusting. In humid regions this period should be reduced. During wet periods and on farms with heavy, sticky soils, it may be desirable to wash and dry implements and to coat all soil engaging surfaces with oil or rust inhibitors on a daily basis.
   - Check wearing parts and replace if necessary.
   - Tighten all nuts and bolts.
   - Grease non-sealed bearings, being careful to first thoroughly clean grease nipples. Sealed bearings should not be greased over frequently and care should be taken not to use excessive pressure when greasing them as this may damage the retaining seals. Also grease bushes on reversible ploughs, etc.
   - Store overnight in a safe, dry place.

1.b. Seasonal maintenance procedures:
   - Thoroughly clean implement and check all parts for wear.
   - Obtain any required replacement parts.
   - Strip the implement completely, wash and clean all parts and use a wire-brush to remove rust, and paint all parts if possible, other than obvious parts like plough discs.
   - Replace wearing parts that have worn beyond acceptable limits.
   - Assemble and adjust the implement. Oil nuts and bolts by oiling threads prior to assembly of nuts and bolts. Oil or apply rust inhibitor to bright soil engaging parts, e.g. plough discs, and also mouldboards and shares if they were not painted.
   - Grease ball and roller bearings, being careful not to apply excessive pressure to sealed bearings. Also grease bushes.
   - Store in a safe, dry place.

1.c. Additional maintenance required for specific groups of tillage implements:

Tined implements:
   - Land wheel bearings, if not sealed, and trip mechanisms should be lubricated on a weekly basis during use.
   - Shares must be replaced, or double ended ones reversed, when their wear limit is
reached otherwise the tine will be damaged.

- Undue side play, at the pivots of spring-loaded tines should be taken up with packing washers.

**Mouldboard ploughs:**

- Grease non-sealed and sealed bearings on land wheels and disc coulters as described above.
  
  NB: Never oil open wheel axles, as on animal drawn ploughs, as this encourages the retention of abrasive soil particles in the axle which increases wear.

**Disc ploughs, disc harrows and ground driven rotary implements:**

- Grease non-sealed and sealed bearings on the discs, tail wheels, and rotary tools, etc. as described above.

- With a new harrow, it is important after the first few hours of work to check the tension on the nuts securing the discs and distance pieces to their central spindles. Whenever these are tightened the nut must be relocked by means of the cotter-pin or tab-washer provided. If the discs develop excessive end-play, their central holes will be enlarged, and the spindles damaged, making tightening of the disc assemblies impossible without reconditioning. New disc ploughs should also be readjusted after the first few hours of work.

- The links connecting the front harrow gangs to the rear should not be lubricated, as this would retain abrasive soil particles and increase wear. Care should be exercised not to damage these links through reversing or turning with the implement in the soil, as the staggering between the front and rear discs will then be altered reducing the intensity of operation.

**Rollers:**

- Various types of bearings are used on roller spindles with differing lubrication requirements. Some are totally enclosed ball or roller bearings, requiring only occasional lubrication, while others are of brass or bronze, and demand daily greasing when in use. NB: The spindle should not be lubricated at the hubs of the actual rings, as this retains abrasive soil that increases wear.

- The end-float of the rings should be checked regularly. Excessive end-float is either taken up using packers or on some models by adjusting the position of the bearings or side cheeks.

**Rotary cultivators and other p.t.o. driven implements:**

- The splines on the p.t.o. connecting shaft should be cleaned and greased on a daily basis. The universal joints on the implement and the p.t.o. connecting shaft should be greased on a weekly basis.

- The blades of rotary cultivators should be checked daily for wear and tightness. They are usually held by two bolts, and one of these sometimes has a lower shear-strength than the other, so that if an obstruction is hit one bolt shears thus removing the loading but retaining the blade. The machine should not be operated with blades missing as this upsets the balance of the rotor, and causes intermittent loading.

- The oil level in the oil baths of the bevel gear box and the rotor-speed gear box should be checked on a weekly basis while in use. The oil should be changed according to the operator manual, and generally at least once a season.

- Covered chain drives should be lubricated on a weekly basis. Exposed long-linked agricultural chains found on some p.t.o. driven implements and planter/fertilizers should not be lubricated as this tends to retain abrasive soil particles in the links that hastens wear.

- Make sure that the implement p.t.o. shaft is off the ground and free of dirt when stored.

- After storage and prior to first use in the season it is important to check the slip-clutch or overload device to ensure that it has not seized.
Implements with hydraulic controls:

- Check for leaks on the pressure hoses and connections and replace the line if it is leaking. Tighten connections if they are leaking and only tighten until the leak stops, replace the washer if it is damaged. Do not bend hydraulic hoses as this will restrict the movement of the oil and damage the hoses.
- Hydraulic jacks are either single acting or double acting. Check for leaks on the cylinders and send for repair if there are any. When lifting fails because of air in the cylinder, bleed the cylinder to get rid of the air. Bleed system on a weekly basis.
- Clean couplings before connecting or disconnecting them to avoid getting dirt into the system, as hydraulic systems are very sensitive to dirt. Always close the female couplings when not in use.

2. Planting Implements:

Follow the manufacturer's instructions for daily, weekly and seasonal maintenance.

2.a. Daily maintenance while in use:

- Generally use same daily and weekly maintenance procedures as used for tillage implements for soil engaging components, bearings, bushes, chains, etc. Care should be taken not to lubricate open agricultural type chains, or open bushes on Pitman Drives. Check wearing parts and replace those worn beyond acceptable limits.
- Empty the seed hoppers and metering devices after the day’s work. Clean and check for blockages in seed tubes and in metering devices, e.g. seeds jammed in cells, etc. Also check tightness of bolts, and fit of cell-plate, etc., in metering device. Generally do not use water to clean metering device on daily basis and ensure that it is dry prior to being stored overnight to prevent rusting.
- Any dog-clutches for engaging the various mechanisms should be kept well oiled and free of dirt.
- Pneumatic wheels should be checked for correct air pressure.

2.b. Seasonal maintenance:

- Generally follow seasonal maintenance instructions for tillage implements.
- Remove all seed hoppers and thoroughly wash them. The seed tubes should be removed and cleaned.
- Chains and gears should be closely examined and adjusted if necessary. Closed chains should be greased or oiled, and open agricultural type chains should be coated with oil to prevent rusting. On the latter this should be washed off at the start of the season to prevent the adhesion of abrasive soil particles to the chain which will lead to increased wear.
- Seed metering devices should be dismantled, thoroughly washed and cleaned, closely checked for wear and reassembled with new parts where necessary. Steel seed plates should be coated with oil or rust preventive, and this should be removed at the start of the season.
- Paint the machine where paint has chipped off or where rust has undermined the paint, being careful to remove all rust first. Coat non-painted components with oil or rust preventive, including coulters, furrow openers, the inside of seed tubes, etc.
- Implements with pneumatic tyres should be blocked up to remove the weight of the implement off the tyres.
- Store in a safe, dry shed, or if this is not available under a tarpaulin.

3. Fertilizing Implements:

Follow the manufacturer's instructions for daily, weekly and seasonal maintenance. For combination planter/fertilizer implements the procedures listed above should also be followed.

3.a. Daily maintenance while in use:
Generally use the same daily and weekly maintenance procedures as used for tillage implements and for planters. In addition it should be noted that fertilizers are generally highly corrosive. Hence after work each day empty the fertilizer out of the hoppers and metering devices, remove agitators, brush out any remaining fertilizer and then wash the equipment with plenty of water.

3. Seasonal maintenance:
- Generally use the same seasonal maintenance procedures as used for tillage implements and for planters.
- In addition the fertilizer metering device should be dismantled, thoroughly washed and cleaned, checked for wear and reassembled with new parts where necessary.


Wear in the wheel bearings should be checked regularly by rocking the wheel in and out by hand, while on the cart or implement. On heavy carts or implements wear can be checked by jacking up the axle to lift the wheel clear of the ground and then rocking the wheel. If free play can be felt then the bearing should be readjusted.

Before dismantling the wheel-hub, the following precautions must be taken to prevent dirt entering, which would considerably reduce the life of the bearing. The cart should be moved onto a clean floor of concrete or sacking and the axle blocked up. Ensure hands and tools are clean and free of sand then partially dismantle the wheel-hub in the following way:
- Remove hubcap and then split pin.
- Tighten the castellated nut until the wheel does not turn freely.
- Turn the nut back between one flat and half a turn, depending on the instructions in the manufacturer's manual, so that the wheel turns freely but without lateral free play.
- Replace the split pin, add extra grease if necessary, and replace hubcap.

The taper bearing should be taken out once a season and checked for wear. Before checking they should be cleaned in petrol or spirits and thoroughly dried. Then both the taper bearings and the bearing race should be checked for wear. This is usually shown up by pitting on the surface or the wearing through of the hardened layer. Grease should be packed into the old or new taper bearing cage prior to reassembly.

Many animal drawn carts use metal bushes rather than bearings. These should be cleaned and lubricated more regularly than roller bearings. Nylon and some synthetic material bearings are self-lubricating and do not require any additional lubrication. However, they should be cleaned on a regular basis. Axles using bushes are frequently of the reversible stub-axle type designed so that they can be reversed and so double the life of the axle. Bushes are much cheaper than axles and should be replaced as soon as excessive play occurs, otherwise rapid wear of the axles will occur.

The wooden components of carts, e.g. poles and cart tops, should be given a coat of creosote or similar preservative on a seasonal basis.

6.2. SAFETY PRECAUTIONS

As stated at the beginning of this section one of the most important resources that farmers have is their own health and that of labourers on their farms. Because of this, and particularly because so many farm machines and implements are dangerous when operated incorrectly, it is essential that safety precautions are observed at all times. While the safety of the operators or third parties is of prime importance, the safety of draught animals and
prevention of damage to tractors and equipment is also of great importance. Hence, safety precautions should be adopted which protect both the human individuals and the draught animals as well as the machinery and implements.

The basic approach to most safety precautions is to assume that if anything can go wrong that it will go wrong. Steps are then taken to ensure that no injury or damage can occur when it does go wrong. In order to achieve this the operators and managers must be encouraged to think logically through the whole process, on a step-by-step basis, that the operation of the draught animals or tractors and implements involves. For every one of these steps they should consider what could go wrong and how the humans, animals, or equipment could be injured or damaged if any one of a number of things did go wrong. They should then devise ways of doing the operation to avoid, or absolutely minimise, any chance of injury or damage. It is important that a common sense approach is adopted.

The operation of manual, animal drawn or tractor drawn implements should be carried out when the operators are alert and rested. Accidents are far more likely to happen when operators are tired and lack concentration. The correct posture of the human body is very important when carrying out physical tasks. When lifting heavy weights the back should be protected by keeping it straight and the bending done with the legs. Wherever possible heavy or tiring manual tasks should be carried out with the person standing upright and the tools should be designed to enable this, e.g. using long handled weeding hoes rather than short handled ones. However, the heavy hoes have to be short handled, but even these can be used in such a way that the back is protected by keeping it straight and tight with most of the bending done from the hips.

Animal handlers should be aware of how the animals are likely to react if scared or aggressive. For example, horses will kick directly behind them, whereas cattle will kick to the side and back. When attaching or disconnecting draught animals to an implement this should be done in such a way that no injury will occur should the animals suddenly bolt. For example, the operator should not stand between the implement and the animals, and their fingers should not be held in between the links of a chain but around the outside so that the chain could simply pull through the fingers.

Besides the above, the main aspect of safety with animal drawn implements is when maintaining them. There are a number of deliberately sharp edges on the implements and it is important when tightening bolts that correctly sized spanners are used that will not slip on the nut or bolt, which would allow the hand to impact against the sharp edge. Care should also be taken when cleaning seed or fertilizer metering devices that the fingers are not in a vulnerable position when the drive wheels are rotated.

The starting and stopping procedures for tractor engines and aspects of their operation, given by AGRITEX TP1 (1986) typify the detailed safety aspects required for these procedures and some of these are listed below:

Starting the Tractor Engine:

Before mounting the tractor, the driver must make sure everyone is clear of the machine and that safety shields and covers are in place. The driver must be in the tractor seat before starting the tractor engine and should carry out the following checks and starting procedures:

- Apply the handbrakes.
- Place gear lever in "neutral", "park" or "start" position.
- Place all hydraulic controls in neutral.
- Check that the p.t.o. is disengaged.
- Keep clutch pedal pressed down to reduce the load on the starter motor.
- Set throttle on 3/4 open and check that the start control knob is in the start position.
- Turn on the ignition switch and pre-heat if necessary until the glow indicator turn red.
- Operate the starter switch that is usually built into the ignition switch. If the engine does not start within thirty seconds, release the starter switch and wait for thirty seconds before trying again.
- Release the clutch pedal and allow the engine to idle for a few seconds before moving off.

Stopping the Tractor Engine:
- Stop the tractor by applying the brakes and clutch.
- Disengage the p.t.o. and lower hydraulically operated equipment to the ground, then put hydraulic controls in neutral.
- Apply the handbrake.
- Put gear lever in "neutral" or "park" position.
- Put the stop control knob in the "stop" position. This will cut off the fuel supply to the engine.
- Switch off ignition and remove key.

Some Safety Aspects of Tractor Operations:

General Operation:
- Drive the tractor when alert and rested. Safe, efficient driving requires concentration and energy.
- Never dismount the tractor whilst it is in motion.
- Obey the Highway Code when driving on public roads.
- No passengers to be allowed on the tractor.
- Keep spanners and other loose items in the toolbox so that they do not interfere with the foot brake or clutch pedal.
- Drive at safe speeds to allow adequate stopping distance in an emergency.
- Reduce speed over rough surfaces.
- Do not drive across steep slopes.
- Avoid the repetitive use of one independent brake during routine ploughing as this tends to unbalance the adjustment. The headland should be wide enough to enable turning without the use of the independent brakes.
- Couple the foot brakes when not operating an implement in the field.

Attachment of trailed and mounted implements:
- Use the drawbar for trailed equipment and the lower links for semi-mounted equipment. Never attach trailed equipment or a towing chain to the top link or above the height of the rear axle as this could possibly result in the tractor tipping up under heavy loads.
- When hitching an implement to tractor drawbar use a jack or block to hold the implement hitching bar at the correct height and reverse tractor to correct position for connection. Then put tractor in neutral and apply hand brake. Do not have an assistant stand between the implement and tractor holding it while reversing.
- The safety regulations regarding tractor drawn trailers for use on public roads are complex and vary from country to country. It is very important that operators are familiar with these regulations. The regulations primarily cover the following; braking requirements, which vary according to the weight of the trailer and its load carrying capacity; lighting requirements; safety chains in case the drawbar connection fails; and rear view.
- When hitching an implement to the 3-point linkage do not have assistant stand between the implement and the tractor while latter is in gear. Connect left link first, then right link and finally upper link.
- Always shorten the top link and tighten the check chains when transporting 3-point mounted equipment.
- Do not mount equipment that is so heavy that it dangerously reduces the weight on the front wheels.
- When a mounted implement is in the raised position the centre of gravity of the
outfit is raised considerably. The outfit is therefore less stable and liable to tip sideways on gradients or when turned abruptly at speed.

- Ensure that no one is standing near the swinging bodies of a stationary reversible plough before tripping the turnover mechanism.
- Support the implement and ensure that it is stable before disconnecting or unhitching.

### Hydraulic system:
- Lower hydraulic units before leaving the tractor.
- Switch off the engine before servicing the hydraulic system.
- Before disconnecting oil lines, relieve all hydraulic pressure in the system by moving the control lever up and down after the engine has been switched off. Ensure that couplings are clean before connecting or disconnecting them. Always close the female couplings when not in use and use dust covers for all couplings.
- Ensure that all line connections are tight and lines are not damaged because escaping oil under pressure is a fire hazard and can cause personal injury.
- Check hydraulic reservoir oil level on tractor and top up if necessary prior to use of hydraulic system.
- Be careful with twisted hoses as they can explode and cause damage.
- Never kneel or sit under a plough held in the raised position by the tractor hydraulic system when carrying out an inspection, fitting shares or making adjustments. The implement may be left attached to the tractor but the tractor engine should be switched off and the implement should be held on stands.

### P.t.o. system:
- Before connecting the implement to the power shaft, disengage the p.t.o. or switch off engine. Switch off engine if performing any work on the tractor or implement. NB: There are several types of p.t.o. and the manufacturer's manual should be consulted to determine the type and the means of disengagement. The main types are as follows:
  - Transmission Drive p.t.o.: The p.t.o. is controlled by the clutch pedal and p.t.o. shift lever. With tractor engine running, press clutch pedal down and move p.t.o. lever to engage p.t.o. drive. Engage or disengage clutch to control p.t.o. rotation.
  - Continuous Running p.t.o.: This type uses two clutches, one for forward motion and one for the control of the p.t.o. The p.t.o. clutch may be operated manually or hydraulically assisted.
- Securely lock the p.t.o. shaft to the p.t.o. stub once the shaft is connected. There are four main types of locking devices, namely; spring-loaded lock pin; steel bolt and nut; steel pin extending through the centre of the shaft; self-locking coupler.
- Ensure that p.t.o. shields are in place.
- Ensure the correct p.t.o. speed is selected. Always depress the clutch pedal when changing p.t.o. speeds or disengaging p.t.o. There are two standard p.t.o. speeds, namely 540 rpm with a stub shaft with 6 splines, and 1000 rpm with a stub shaft of 21 splines. Some tractors are fitted with both stubs or the stubs can be interchanged. It is very important that the implements are operated at their correct rotational speed.
- Keep hand, feet and clothing away from rotating p.t.o. shafts. Wear sensible work cloths, not loose clothing.
- Keep the p.t.o. stub on the tractor protected with the shield and guard when not in use.
6.3. PROGRAMMES TO IMPROVE CARE AND MAINTENANCE OF FARM IMPLEMENTS AND ADHERENCE OF SAFETY PRECAUTIONS

As pointed out at the start of this section, in order to be able to implement the various tillage and cultivation operations in a timely, efficient and cost effective manner it is essential that farm equipment is properly cared for and maintained. Because of the importance of care, maintenance and safety, and also because of the large number of factors involved, it is highly desirable to tackle problems in these areas in a comprehensive manner. These aspects would be included in any national mechanisation strategy, but if this has not been carried out a similar formulation procedure can be carried out. Strategy formulation was discussed in Section 2.2.3. and the same principles apply here. As mentioned there, if it is not possible to develop and implement a full national strategy then it is still highly desirable to develop and implement specific action programmes which address the main constraints to improved care, maintenance and safety.

The starting point for strategy formulation is generally a review of government policy documents and the government's National Development Plan. These plans generally state what needs to be done. However, where these plans are not sufficiently specific then the strategy document should specify what needs to be done. The strategy then describes how it is to be done, by whom, when, and in what order. As Gifford (1981) points out the strategy document is a blueprint for action, a procedural manual for the daily guidance of all those inside and outside government service that have to make a decision.

When developing programmes to promote a desired change it is very important to consider the infrastructural support required, e.g. improved training/extension infrastructure, any foreign exchange implications, etc. A full discussion is beyond the scope of this publication, but it is considered important that extension workers are aware of the logical framework and range of intervention measures that are available to address the problems, both on an individual farm basis and on a national level. It needs to be emphasised that the main constraints to improved care, maintenance and safety in a particular country should be identified prior to the development of any intervention measures.

Approaches to improving the care and maintenance of farm machinery, and the adherence of safety precautions, are listed below without further comment. These are likely to be closely associated with, or included in, programmes to promote the knowledgeable selection, operation and adjustment of farm machinery. A few of the points listed are only relevant to literate farmers or to the more expensive categories of equipment.

A. Promote general awareness of the importance and detail of the issues involved:
   1. Ensure subject covered adequately by the training and extension services.
   2. Ensure that regular periodicals are established on care, maintenance and safety, aimed at all organisations involved, including dealers, local representatives of farmers' unions, etc. List and analyse local problems, recent accidents, etc.
   3. Ensure that local farmers' magazines cover the subject and receive contributions from the extension organisations.

B. Improve the training of, or extension to, farm managers and operators:
   1. Ensure training of trainers is of a good standard.
   2. Provide well staffed and equipped, fixed and mobile training facilities.
   3. Promote attendance on courses or group visits.
   4. Ensure follow up by extension staff.

C. Increase the farmers' awareness of the important selection criteria for the purchase of
farm equipment, other than cost and use, e.g. durability; efficiency; ease of operation, adjustment and maintenance; and safety; etc.:

- Include the criteria for selection in training/extension messages.
- Encourage manufacturers to make available the required information.
- Ensure that information from test centres is available to the farmers.

D. Improve the on-farm management, operation, care, maintenance and safety in use of farm equipment:

1. Improve training of, or extension to, farmers, farm managers, operators in these areas.
2. Encourage manufacturers to provide detailed operators' instructions for the use and maintenance of all equipment sold. Programmes to assist some manufacturers of implements for the small-scale sector in the preparation of this material may be required.
3. Promote forward thinking and planning to ensure that equipment is available and in good operating order when required, through the promotion of:
   - The use of maintenance schedules to guide maintenance.
   - Keeping good records of equipment use, breakdowns, costs, etc., and their use to analyse costs, efficiency, etc., and to plan future maintenance requirements.
4. Promote establishment of an ethos of good care, maintenance and safety, through the promotion of:
   - An understanding of the advantages involved.
   - The development of pride in being skilled in the operation and maintenance of equipment.
   - Allocation of one operator per tractor so that it is easier to apportion praise or blame for good or poor performance and longevity of equipment.
   - Pay incentives to promote good care, etc.
5. Promote the provision of good on-farm maintenance and storage facilities, where these are economically viable.

D. Improve availability of spares, tools, lubricants, etc.:

1. Facilitate local manufacture or importation of required spares, etc.
2. Facilitate the expansion of viable dealership networks.
3. Facilitate improved transportation links to rural areas.
4. Facilitate improved credit facilities.
5. Encourage dealers and manufacturers to provide exploded diagrams of implements, and labelling of parts, to facilitate correct identification of parts required.

E. Improve off-farm service and maintenance facilities:

1. Facilitate availability of spares, etc.
2. Facilitate the expansion of dealership networks and independent workshops providing service and maintenance facilities. The complexity of the workshops may vary from tractor maintenance level to blacksmiths’ shops depending on the requirements.
3. Facilitate technical assistance from richer to poorer farmers to provide these services for barter, grazing rights, etc.
4. Facilitate improved transportation links to rural areas.
5. Facilitate improved credit facilities.

F. Improve the quality, ease of operation, adjustment, and maintenance, and the safety of farm implements:

1. Improve feedback from operators and farmers to dealers and manufacturers regarding problems encountered by farmers in the use of their implements.
2. Encourage manufacturers and dealers to establish improved links with farmers to promote this exchange.

The above outline is not exhaustive and some additional activities will be required depending on the specific constraints identified. Furthermore, the logical framework given above is not rigid and variations may be desirable for specific conditions. It must also be emphasised that the above outline does not detail the extensive infrastructure required to implement a comprehensive programme.
7. THE COSTING, PLANNING AND ACQUISITION OF FARM EQUIPMENT

The investment and operating costs of farm equipment are very important factors used in farm planning and management, which includes the selection of tillage systems and crop cultivation and management systems. This is because the financial viability of various farm enterprises, and particularly crop production, is usually heavily dependent on the costs of the farm equipment and labour costs used to implement them. Another closely associated factor is the work rate of the equipment, which largely determines the labour costs. Furthermore, the work rate of a piece of farm equipment to undertake a particular operation is usually closely associated with the investment cost of the equipment. This section will briefly cover the way in which equipment costs are broken down and their main characteristics. Also covered is a brief comparison of the costs of cultivation operations using manual, animal and motorised power sources, and a brief outline of machinery planning and the various methods of acquiring the use of farm equipment.

The broader economic framework in which farms operate, and in which tillage, cultivation and management systems are chosen, was briefly covered in Section 2.5. One aspect of particular importance discussed there was the difference between the resource-poor and resource-rich farmers in terms of their farming objectives and strategies. It is important that these aspects are borne in mind while considering the more technical details of machinery costing and its acquisition that is covered in this section.

A large number of publications cover the basic principles of farm economics and the investment and operating costs of farm equipment and these include Buckett (1988) and Culpin (1975). The following sections are based closely on Buckett (1988).

7.1. THE BASIC PRINCIPLES OF COSTING FARM EQUIPMENT

The costing of farm equipment is carried out within the context of determining the costs of production, i.e. the cost of producing a certain amount of product in a given time. These costs are divided into two main forms, and the definitions and notes given below are based on Buckett (1988):

- Fixed Costs:
  Costs that are incurred irrespective of what production, or more specifically what output, is obtained, at least in the short run. For example, rent for land and buildings, regular labour, and depreciation on machinery.

- Variable Costs:
  Costs that vary with the scale of production, generally only being incurred if production takes place. They generally vary directly with the level of output. For example, fertilizer, seed, fuel, maintenance, additional short-term labour costs required for the implementation of the operations.

It is useful to note that if the resources represented by most fixed-cost items are not used at the time they are available they are lost forever, e.g. when labour, draught animals and tractors are under-utilised, or buildings are left empty. (Note: This generally applies to tractors and machines because the depreciation is generally calculated over a set number of years which is independent of the number of hours worked. Hence, the depreciation is lost whether the tractor is used or not. This analysis may not be appropriate where spares are difficult to obtain, and where the life of a tractor may be eeked out to cultivate only valuable crops, etc.).

By contrast, the resources represented by most variable costs can be stored for the future if not employed at once, e.g. fertilizer, fuel. The way in which fixed and variable costs are used in farm management means that there are exceptions so it is not wise to always use this difference in the definition of fixed and variable costs. For example, fencing costs are treated as fixed, but fencing materials can be stored.
Prior to proceeding it will be useful to define several other costs and terms:

- **Capital Investment Costs:**
  The interest charged on bank loans, hire purchase, etc., used to raise the capital to purchase assets. If the assets are purchased out of the farmer's own funds then usually an opportunity cost is charged.

- **Opportunity Costs:**
  When money is invested in an asset or enterprise it means that the money cannot be invested in a bank or another enterprise in order to earn a return. The loss of this potential return is called the opportunity cost.

- **Depreciation:**
  This is the reduction in value of a fixed asset due to use, obsolescence, etc.

- **Amortization:**
  The money used to write off the value of a depreciating asset by annual transfers to a sinking fund. The amount of amortization accounts for both the depreciation and the investment or opportunity costs.

- **Unit Costs:**
  These are the costs of an operation per hectare, or unit area, including both fixed and variable costs. The larger the area over which the machine is employed the more its costs are spread and the lower the unit costs.

Calculating the cost of equipment over time, i.e. compiling a machinery budget, is carried out for a number of reasons, including obtaining data for an economic analysis of particular production enterprises, calculating tax allowances, establishing the costs of purchasing a particular machine, comparing the relative merits of different machines, calculating charges to be imposed by contractors for particular operations, etc. Budgets can vary in their accuracy in so far that the most simple may only produce crude answers, which might be sufficient to give a basic appreciation of the situation, whereas the most accurate budgets can be detailed and time consuming.

The following derivation of a simple machinery budget is given based on Buckett (1988), but using the example of tractor ploughing in Malawi using information given by Morris and Bishop (1992), where the unit of currency is the Kwacha (K):

Data used:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tractor purchase price</td>
<td>K95000</td>
</tr>
<tr>
<td>Plough purchase price</td>
<td>K15000</td>
</tr>
<tr>
<td>Residual value</td>
<td>10% purchase price</td>
</tr>
<tr>
<td>Economic life</td>
<td>10 years</td>
</tr>
<tr>
<td>Variable costs</td>
<td>K120/ha</td>
</tr>
</tbody>
</table>

A. **Fixed Costs:**

1. **Depreciation:**
   The first step in calculating the cost of equipment use is to calculate the depreciation. The economic life of the tractor and plough is determined to be about 10 years, with a residual value of 10% of purchase price. A linear reduction in value is assumed here.
   Annual Depreciation = (Total cost - Residual value)/life.
   Depreciation = (K110000 - K11000)/10 = K9900 pa.

2. **Investment or Opportunity Costs:**
   The interest on the capital could be based on the initial capital, but this might be considered unfair, as profits could be used annually to pay off this debt. The depreciation charged to the profit and loss account is purely a notional item and no money is actually spent on it. This depreciation figure can therefore be regarded as
reducing the bank overdraft each year and hence the interest payable on the capital still invested in the machine. To obtain a fully accurate position for each year it would be necessary to undertake annual budgets. Many people overcome this by taking the interest on the average capital invested in the machine, assuming zero final value, i.e. \((\text{Initial capital} + 0)/2\). Since many machines are sold before they are fully depreciated, some farmers modify this calculation and fix the capital on which interest is to be charged as \((\text{Initial capital} + \text{Residual value})/2\). This type of "average position future" calculation is sufficient for many farmers, but others require greater accuracy. Discounted cash flow techniques, described by Buckett (1988), permit calculations to be undertaken more accurately on a year-to-year basis. They also allow tax relief on interest actually paid, to be taken into account.

Average capital invested \(= (\text{Purchase cost} + \text{Residual value})/2 = (K110000 + K11000)/2 = K60500\)

Where a farmer does not need to borrow to finance the purchase it is still common practice to charge an opportunity cost on the capital invested in the machine.

3. Table of Fixed Costs (Annual):

<table>
<thead>
<tr>
<th>Annual Fixed Costs</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depreciation, pa.</td>
<td>9900</td>
</tr>
<tr>
<td>Interest on K60500, @ 8%</td>
<td>4840</td>
</tr>
<tr>
<td>Other fixed costs, e.g. insurance, say 1% of total purchase price</td>
<td>990</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15730</strong></td>
</tr>
</tbody>
</table>

B. Variable Costs:

1. The variable costs of operating the tractor and plough, including fuel, maintenance, etc., were calculated to be K120/ha.

C. Total Costs:

1. If the machine was used on the following areas the cost per hectare would be:

<table>
<thead>
<tr>
<th>Area (ha)</th>
<th>10</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total annual fixed costs (K)</td>
<td>15730</td>
<td>15730</td>
<td>15730</td>
</tr>
<tr>
<td>Fixed cost per hectare (K)</td>
<td>1573</td>
<td>315</td>
<td>157</td>
</tr>
<tr>
<td>Variable cost per hectare (K)</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td><strong>Total cost per hectare (K)</strong></td>
<td><strong>1693</strong></td>
<td><strong>435</strong></td>
<td><strong>277</strong></td>
</tr>
</tbody>
</table>

The above results demonstrate the high unit costs resulting from under utilizing machinery that is owned by the farmer and has a high purchase price.

A machinery budget would also be used by a contractor to calculate the cost of carrying out a particular operation. The cost charged to the customer would be based on the anticipated annual usage and would include the cost of travelling to and from the customer's farm as well as the provision for the required profit. The more detailed analysis mentioned in the following section would generally be used by contractors.

7.2. COST COMPARISONS OF MANUAL, ANIMAL AND MOTORISED POWER SOURCES
Using a more detailed analysis than that described above, Morris and Bishop (1992) compared the costs of manual, animal and motorised power sources in Malawi, as part of the development of a mechanisation strategy for the country. The results of their calculations for animal and tractor draught power sources are shown in Tables... (Morris 1992, p vii.10, Table 2 and p vii.13, Table 3). From the tables the parameters used in these analyses can be seen together with some typical comparative values.

These results, for each of the various power sources, were then used to compare the cultivation costs for seedbed preparation in terms of costs per hectare by area cultivated, as shown in Figure... (Morris p vii 17, fig. 1). As Morris and Bishop (1992) point out, direct comparison between the power sources is difficult as the farming systems they are used within vary with the power source used. For example, hand methods dig and reform ridges; oxen plough and ridge; tractors plough, harrow and ridge; and power tillers make two passes with the rotovator. Furthermore, the cultivation systems vary in terms of depth and quality of soil preparation and their suitability to particular soil type and moisture conditions. Power tillers, for example, are suited to irrigation rather than dry land farming.

When analysing the results shown in Figure... (Morris p vii 17, fig. 1) the relative order of the estimated cultivation costs is generally more relevant than absolute cost estimates. The different way in which the costs of owned and hired draught power sources vary with cultivated area is apparent. The cost of owned draught power sources initially decrease exponentially as the area cultivated increases, because the fixed costs are spread over a larger area, i.e. the unit costs decrease. By contrast, hired power is commonly hired on a time or area basis and is therefore a straight line on the graph.

A more detailed analysis of Figure... (Morris p vii 17, fig. 1) is instructive, however it must be emphasised that the data is particular to the area in which it was collected. Morris and Bishop (1992) observed that over 90% of smallholders have farms of less than 2 ha, and at least 95% are below 4 ha. For this situation they observed that the least cost systems are hand power, followed by owned and hired oxen. Hand power tillers (for irrigated farming) are expensive, as is conventional tractor hire. For most small farmers hand labour and animal power systems are most relevant. It can also be seen that the economic capacity of an oxen team is about 4 ha, but farms with 2 ha could find draught animal power ownership attractive if they could provide some contract hire work.

The estimated cultivation costs are useful for determining the financial feasibility of introducing upgraded mechanisation systems, in terms of the additional product output that would be required to justify the switch from one system to another. Increased product output may be achieved either through increased yield or the increased area cultivated or both. Generally, improved mechanisation leads to higher yields primarily through improved timeliness and secondarily through improved quality of operation. The objectives of mechanisation were discussed in Section 5.1.

7.3. MACHINERY AND IMPLEMENT PLANNING

As Buckett (1988) points out, there is an optimum level of mechanisation for each farm and ideally this level should be selected as an integral part of the overall farm plan. Many machinery planning techniques have been developed, however, these are generally only used for planning on large-scale farms. In practice a high proportion of machines are selected on the basis of personal judgements based on previous experience, related to such factors as the labour and work days available, together with the requirements of the enterprises to be undertaken on the farm.

Each farmer has to decide how much agricultural equipment to have, and for machines this includes the size and capacity of the individual machines. A decision also has to be made
as to whether to purchase the equipment or to obtain them by some other means such as leasing. This section will deal briefly with primarily motorised draught power and equipment, but similar principles apply to animal draught power and equipment.

7.3.1. Machinery Capacity

Machine and implement capacity is a term covering the work rate capability of a particular machine/implement combination or the capacity of all equipment on the farm that have the same function. For tillage implements and their draught sources machine capacity is usually measured in units of hectares per hour. This information was given for a wide range of tractor and animal drawn tillage implements in Sections 5.3.1 and 5.3.2, at the end of the description of each tillage implement. The power requirements for the implements were also given, generally in terms of the net tractor engine power required per meter of implement width. Additional information on the time taken to carry out various tillage operations using manual labour and animal drawn implements was given in Section 5.2.1. Additional sources of information are FAO (1990), Agritex (1982) for agriculture in subtropical regions, and Culpin (1975) for agriculture in temperate regions.

Another means of selecting the required size and capacity of equipment is to determine the work per hectare, in terms of kWh/ha, required for the various operations on a farm. The total requirement, and particularly the requirement at times of the year when equipment demands are highest, is used as a guide to selection. For tractors it should be remembered that for every unit of power available at the flywheel, i.e. net engine power, only 80%, and in many cases less, is available by the time it reaches the back wheels because of internal transmission losses. Further losses due to wheel slip and rolling resistance have to be added to these losses before the power for effective work can be estimated. This aspect was covered in Section 5.2.3.

Most farmers do not employ the sophisticated methods outlined above. They identify the peak periods of demand for machines, usually based on past experience, and then consider the whole machinery system in relation to these. However, the capacities of the most important machines still play a large part when the final selection is made. The selection of the crops to be grown and the tillage system and crop cultivation and management systems to be used are important means of reducing the peak machinery capacity demand and of spreading the demand more evenly over the year. These aspects were discussed in Section 3 and in particular in Section 3.2.2.

The farmer also has to decide whether to base the machine capacity on the requirements of the average year or to have extra capacity to allow for seasons where adverse weather conditions may restrict the time available to implement operations. This is important because the timely implementation of crop operations usually has a significant effect on yields, and is largely determined by the availability of adequate machine capacity and labour. The farmer's attitude to risk is therefore relevant.

Standard data for machine capacity should be treated with caution for several reasons, including the following; the effect of different soil types and soil conditions on the draught power requirements of implements, as well as on the draught power available from tractors of a given power; the variations in weather patterns and the affect of moisture on different soil types; the skill with which a machine is used; the state of repair and maintenance of the machines which is also affected by the local supporting infrastructure for mechanisation; the shape, size and conditions of the fields; etc.

7.3.2. Machinery Selection
A large number of criteria need to be considered with regard to the selection of machines and implements, and some of these are listed below:

- The power sources and implements chosen should be the most cost effective solution to meeting the implement or machine capacity requirements of the farm. Manual, animal and machine power sources should be considered where appropriate. A large 150 kW tractor may be the most appropriate power source for a large farm and manual power the most appropriate power source for a small farm.

- The draught power sources and their associated implements should be compatible with each other in terms of power, hydraulic requirements, p.t.o. shafts, attachments, etc.

- The machine combinations selected for one operation should ideally be compatible with those selected for other operations, unless this reduces the efficiency of any of the operations. For example, the matching of a tractor to the power requirements of the tillage implements and also to, say, a forage harvester, would allow the efficient use of the tractor over a larger part of the season.

- With regard to the selection of specific makes and models the following points are generally important:
  - Performance and quality of work. Obtain test reports if available, attend demonstrations, and observe machines on neighbouring farms.
  - Purchase price and the price in terms of power or output per unit cost, and the resale value.
  - Terms of warranties.
  - Availability of spares.
  - Service and maintenance requirements, in terms of frequency, the ease with they can be carried out, and their costs.
  - Existence of locally available service, maintenance and repair facilities. These facilities are more likely to be available for common makes.
  - The new machine should fit in with the existing machines and implements on the farm.

- Some makes of machines may be offered at very competitive rates in order to get market penetration in a new area. If it is a new design that has not been thoroughly tested on other farms it may prove to have limitations and its resale value may be low. Changing makes of machines may also lose the goodwill of local dealers, and getting repairs done promptly could be difficult.

7.3.3. Machinery Running Costs

Once a farmer has purchased machines and implements there are several fixed and variable costs to be considered, including, depreciation, interest on capital invested in machines, routine maintenance, spares, repairs, and fuel costs. Several of these have been briefly discussed already.

Figure ___(@ Buckett 1988, p 198, fig. 72) gives estimates of the useful life of different types of machinery and this information can be used for general planning purposes and for the calculation of depreciation. Figure ___(@ Buckett p 199, fig. 73) suggests depreciation figures for various categories of machines according to the frequency of renewal. Figure ___(@ Buckett p 201, fig. 74) gives estimates of the annual cost of spares and repairs as a percentage price at various levels of use. It needs to be emphasised that these figures have been derived from data on the use and costs of machines and equipment under temperate farming conditions, particularly in Britain. However, where full local information is not available this data may give a guide to machinery planners. Some comparable information for subtropical farming conditions in Zimbabwe is given in Agritex (1982).

7.3.4. Machinery Replacement
Many techniques have been developed to predict the optimum time to replace farm machinery. The various techniques will not be described here and only the main factors involved will be outlined, based on Buckett (1988).

Repair costs tend to increase as machines get older and there comes a point when replacement is more cost effective in the long-term than retaining the old machine. Much will depend upon the type of equipment involved and the extent to which care and maintenance can reduce the need for repairs. The amount of use and the effect of breakdowns on specific farming operations, and the increased risk of this happening with age, must feature in any replacement policy.

As they age, machines may become obsolescent, the cost of which can be difficult to evaluate. Tax considerations play a big part in large-scale farmers' replacement decisions. Many look at their possible profits shortly before the financial year end to assess the tax saving that would be derived from buying machinery. They should also look at their cash flow to determine whether the business can afford the purchase and should establish that alternative investments would not be more worthwhile.

The time of purchase in relation to the economic climate may be important. Discounts or trade-in values on old machines may vary during the year. During times of inflation prices rise substantially, although second-hand values should also rise. If the purchase is to be delayed the farmer should determine if the cash will be available the following year to buy the machine and assess the trend in interest rates if capital has to be borrowed, as well as consider the previously mentioned points. Farmers may also consider the motivational influence of new machines on their staff.

7.4. METHODS OF ACQUIRING THE USE OF FARM EQUIPMENT

Several methods of acquiring the use of farm equipment exist and these are listed below and discussed in this section:
1. Ownership by purchasing using own capital or bank loan.
2. Hire purchase.
3. Contract hire, in various forms.
4. Leasing.
5. Machinery syndicates or co-operatives.
6. Machinery rings.

The first two methods listed above result in farm equipment primarily being used on the farmer's own land, whereas methods 3 to 6 result in the farm equipment being used on a number of farms. These latter methods are frequently classified as multiple-farm-use of machinery. This distinction is particularly important from a national or regional point of view to planners in those countries where there is a shortage of draught power. For example, in some of these regions it may be desirable to spread the benefits of motorised draught power over as many farmers as possible for primary land preparation through the use of one or several multiple-farm-use of machinery systems, and for the farmers to rely on manual and animal power sources for the rest of the cultivation operations which require less draught power. It should also be noted that even in highly mechanised countries, such as Germany, well organised machinery rings are very common and that they significantly reduce the machinery costs of farmers on the smaller farms. Multiple-farm-use of machinery systems are described in detail several publications, including FAO (1985).

This section will primarily look at the alternative methods of acquiring the use of farm equipment from the point of view of the farmer and is based closely on Buckett (1988). Before deciding which method to adopt the following points should be considered:
- Capital: How much is available, what alternative investments exist for it, and how much
will it cost if borrowed?

- Taxation: Which method would possibly save the most tax?
- Capacity: Can a machine of adequate size and performance be obtained?
- Labour: What is the impact of the various methods on periods with peak labour demands and on the quality of work?
- What is the reliability and availability of machines obtained by the various methods?
- Who is responsibility for repairs and maintenance?
- What are the unit costs of the various methods?
- What other specific benefits are there?

In addition to the above points and the following discussions, it is important to consider the local traditions in many countries for the hiring of labour and equipment. One of the common features of many of these traditions is that payment is frequently not in the form of cash. Payment for the use of a neighbour's draught animals and plough may be in the form of labour at a subsequent date, or fodder or grazing rights if communal grazing is not practised. Payment for labour may be in the form of returned labour at a later date, or in beer or other produce, etc. When promoting mechanisation in areas where these systems occur they should be closely studied to determine whether they can be used. The discussion below is primarily geared towards the acquisition of farm equipment in developed cash economies, but many of the characteristics of the different methods also apply to the more traditional systems.

7.4.1. Ownership by Purchase

There are several advantages of ownership by purchase, including the following; this gives control over the availability of the machines and although they are subject to breakdowns careful maintenance will maximise reliability; greater control over the quality of work than if a contractor were employed; the opportunity to contract the equipment out to other farmers; the unit cost may be less than for other sources, but this will largely depend upon the area on which the equipment is used in relation to its capacity.

The disadvantages include the following; the high capital cost, which might be at the expense of profitable alternative investments; the high cost of borrowed money; the possibility that the farmer may not be able to afford the size of machine that is desirable and so getting a smaller one in which the speed and work performance is limited; the maintenance and repair of machinery; the provision of operators.

The purchase of second-hand equipment should be considered, especially where capital is limited, but the increased maintenance and repair costs should be borne in mind. One advantage of the purchase of second-hand equipment is that the main loss in resale value usually occurs within the first few years of use of new equipment.

Taxation may be an important consideration as it can substantially reduce the cost of equipment ownership. Interest on money borrowed to purchase machines is usually allowed by the government revenue department as a cost, which then reduces tax. However, the rate at which the farmer pays tax determines how much can be saved, and the initial cost of the machine still has to be found.

7.4.2. Hire Purchase

The main advantage of hire purchase is that the full cost of the equipment does not have to be found at the time of purchase, however a deposit of up to one-third is usually required. The total cost is extremely high because interest is charged on the initial principal throughout the term of the agreement. This agreement usually lasts 1 to 3 years, and the true interest rates are well above those for a bank overdraft. This method confers many of the
advantages of ownership, but there is a great danger of becoming over-committed to hire purchase.

With regard to taxation, although a farmer does not technically own a machine bought by hire purchase until the agreement is completed, a wear and tear allowance can be claimed from the outset, and the interest, but not the capital, part of the instalments can also be claimed as a cost.

7.4.3. Contract Hire

There are several advantages to the use of contract hire arrangements as opposed to purchasing equipment, including the following; the farmer's need for capital is reduced; interest charges on borrowed capital are reduced; more funds may be available for investment in other productive areas of the farm; in some cases total farm machinery costs are reduced; the contractor is responsible for repairs and maintenance; the contractor may provide a larger machine than the farmer could afford to purchase, thus improving the timeliness of operations and may also allow the farmer to grow a larger area of a particular crop; and if the farmer should decide to change the enterprises on the farm the services of the contractor can easily be dispensed with.

There are two main disadvantages of the use of contract hire. Firstly, the contractors are not always available when required and losses may result for those operations in which timeliness is important. Secondly, the farmer has less control over the quality of work. Generally, a better service may be provided if a large area is offered for contract, especially if cultivation, seeding and harvest are involved.

The main forms of contract hire for equipment are discussed below and these points are in addition to the advantages and disadvantages listed above:

a. Short term hire over a period of days or weeks with associated labour:
Many contractors offer very good service and a wide range of machines. The labour supplied by the contractor adds to the farm staff complement, and may be very experienced and produce a high quality of work.
In several countries government subsidised and run services are provided as part of rural development programmes. However, many of these schemes have been abandoned due to the poor utilization of the capital resources and the generally poor service provided.

b. Short term hire but without labour:
This form of hire is common in many countries. It is particularly useful if the machine required would be used for a limited period of the year and if purchased would remain idle for long periods.

c. Contract hire over a period of 2 to 3 years:
This form of hire is less common but is sometimes provided, especially for tractors. Profit to the hire firm may be limited, but they often consider that their customers will buy other machines from them. Also, because of extra throughput, they recognise that their service facilities will be better utilised. This is because in addition to licensing appropriate machines, the hire company agrees to repair and maintain the hired machines, and to replace them in the event of breakdowns. Availability and reliability are both good. The hire charge is tax deductible and the farmer does not have to find the high initial capital for purchase. It may also be possible to obtain a larger machine than could be purchased outright. However, the total cost can be very high and the saving through tax will depend upon the farmer's tax liability. Furthermore, at the end of the agreement the machine must be returned and there is no allowance for its value.
7.4.4. **Leasing**

Machines are generally leased for 2 to 3 years, with the farmer responsible for licensing, repairs (except those under warranty), maintenance, insurance, and spare parts. In the event of a breakdown a new machine is not supplied. The leasing company retains ownership, but at the end of the contract the farmer may be allowed to keep the equipment at a nominal annual charge. Alternatively, it is returned to the dealer for sale and the farmer obtains a high percentage of the proceeds that could be put forward towards the lease of another machine.

Many different types of leasing agreement exist. Leasing charges are based on the fall in value of the machine over the period of the lease plus an interest charge for the capital invested by the leasing company. Frequently an initial payment, equivalent to 4 months' rent, is required which is offset by a free period at the end of the lease.

The advantages of leasing include the following; the high initial capital is not required which can be particularly beneficial to a farm that is expanding; the machines are replaced regularly and have the availability and reliability usually associated with ownership; and forward budgeting is assisted since future payments are known. The disadvantages are that the leasing costs are higher than employing capital from a bank, although tax advantages must be considered.

All lease and interest charges are tax deductible. The amount of tax saved significantly affects the merits of leasing. Leasing charges usually include purchase tax, and although they can be claimed back, they do enter the cash flow.

7.4.5. **Machinery Syndicates or Co-operatives**

Machinery syndicates, or co-operatives, consist of a group of farmers who join together for the purchase and use of machinery and equipment. Their main aims are to share the cost of purchase and to reduce unit costs by maximising the use of the machines. A syndicate may operate more than one machine or piece of equipment, and this equipment may include stationary items such as grain driers or storage plants.

The ways in which the costs of the machines are divided amongst the members of the syndicate varies with the initial cost of the machines or equipment, usually as follows:

- **Inexpensive machines**: The purchase costs may be divided into simple fractions and the running costs may be split according to each member's use in terms of time, area or weight.

- **Expensive machines**: A more accurate division of purchase costs is usual on the basis of each member's expected use. The running costs are then charged in two ways. First, any farmer using the machine in excess of their initial estimate is charged on the excess at commercial rates. Secondly, the remaining costs less these excess charges, are then divided in proportion to each member's share of the cost of the machine.

- **Very expensive equipment**: For this type of equipment, such as grain-drying and storage plants, the initial cost is again shared in proportion to each member's estimated use. All work is charged at commercial rates, and any surplus is returned to the members in proportion to their share in the syndicate.

The main advantages of machinery syndicates include the following; the purchase costs are shared between the members and the unit costs are reduced; the syndicate may have a better chance of obtaining credit than individual farmers with the result that each member has more of their own capital for other purposes; frequently the syndicate can justify and afford bigger machines than individual farmers could with associated advantages in timeliness; generally the system is more reliable than the use of a contractor; the machines are
usually well maintained and because of good trade-in values it may be possible to trade them in more frequently; the system promotes labour sharing.

The loss of independence to the individual farmer sharing a machine in a syndicate can be a disadvantage if two people require a machine at the same time. For operations where timeliness is important this can present problems and it is important that the management systems set up by the syndicate adequately address these situations. The care and maintenance of machines is also important and this is often addressed by making one member responsible for repairs and the supervision of maintenance. To avoid the possibility of one farmer causing more damage to a machine than others, some syndicates arrange for one person to operate the machine on all farms. A qualified mechanic may be asked to inspect the machines periodically.

A very important aspect of machinery syndicates or co-operative is that they require very good management and organisation as well as good will on the part of the members for them to operate efficiently. It is essential that some of the members are good organisers and that good management systems are established which are acceptable to all the members. Because of this latter requirement it is important that these management systems are agreed upon by the members prior to the purchase of equipment or to the final selection of the members of the syndicate.

7.4.6. Machinery Rings

Machinery rings consist of a group of farmers who arrange that all or most of the members in the ring will provide some of their own equipment for use on the farms of other members in the ring. Machinery rings are very similar to machinery syndicates except that each item of machinery or equipment is purchased by an individual farmer. Each member ensures that the equipment that they purchase is complementary to the pool of machinery available to the machinery ring members.

As the members of the ring are supplying services to each other the cost of the services are frequently paid for in coupons or kept on account. Payment in cash is often only made at the end of the financial year, or at set periods, to balance the account.

Machinery rings have features of both machinery syndicates and contract hire services and their advantages and disadvantages reflect this position. They are very similar to machinery syndicates in that a good management infrastructure and the goodwill of the members are very important prerequisites for their success.
8. **ON-FARM CONSTRAINTS AND OPPORTUNITIES IDENTIFICATION**

The previous sections have dealt with the various components of soil tillage and related aspects of crop cultivation and management. Each of these components has been dealt with in depth and in a compartmentalised manner, although the interactions between the various components, e.g. between soils, climate and economic considerations, have been emphasised throughout. This section outlines the approach that the extension worker is recommended to take when advising farmers on constraint and opportunity identification, primarily relating to soil tillage and crop cultivation and management practices, and attempts to draw together the main components of soil tillage discussed previously. The final section will deal with an overview of the selection of tillage operations and systems appropriate to a particular situation, and is to some extent a very brief summary of all the foregoing information.

When identifying constraints and opportunities relating to soil tillage within a farm it is essential to do this within the context of the whole farming system. This is because tillage is a basic component of the farming system and many of the other components of the system interrelate with the tillage operations and systems. If tillage is treated in isolation from these other components then incorrect tillage constraints and opportunities are likely to be identified. Furthermore, it is important that constraints are not only sought in the enterprises currently being undertaken by the farmer, but that the enterprises are also studied to determine whether they are the most appropriate ones to meet the objectives of the farmer.

Another important reason for treating tillage within the context of the farming system is that the Farming Systems Analysis approach can then be used and the diagnostic tools of this approach are well documented. This approach is summarised in the next section and is followed by the identification of some specific constraints and opportunities.

Prior to proceeding it is worthwhile reflecting that all production processes have natural or economic constraints somewhere within them. If this were not so then the output of these processes could be infinite. At every stage of a process there are a number of factors involved and usually one of these factors is more limiting on growth than others. Natural limiting factors may be the length of the growing period, or the amount and distribution of rainfall at a particular location, or the maximum yield of a specific variety of crop determined by its genetic make up, etc. Economic limiting factors are usually based on a cost-benefit analysis and production functions, such as fertilizer application rates, etc., see Section 2.5. What is of interest here is to discover the particular constraints that result in outputs significantly below the level that could be expected for the given local conditions, resources and aspirations of the farmer.

8.1. **FARMING SYSTEMS ANALYSIS**

As Friedrich (1988) points out, Farming Systems Analysis (FSA) emerged in response to the reluctance of many small-scale farmers to adopt technologically superior practices into their farming systems during the Green Revolution. The reasons for this behaviour were traced to technologies and accompanying services and policies that were incompatible with the natural, cultural and socio-economic environment in which the farmers operated. FSA is particularly relevant to the small-scale and resource-poor farmers as the various components of their farming systems are more closely interrelated and restricted than large-scale farmers. As discussed in Section 2.5 there is a close link between the farm-household and the farming system and both of these are incorporated in FSA. FSA is described in numerous publications including Collinson (1983), Norman and Collinson (1985), and Friedrich (1988).

Employing the full FSA approach is time consuming and requires the establishment of a multidisciplinary task force. This is worthwhile if, for example, a new research thrust or significant change in extension emphasis is to be made. In these cases groups of farms typical of the region are studied with the aim of identifying constraints and opportunities relating to the
whole farming system, or to specific components, such as a specific crop, soil conservation, pest management, etc. This information is then extended to a large number of farmers operating in similar environments. The full FSA approach would also generally be justified if the tillage component in the farming systems was the prime target for change because, say, the commonly used tillage system was leading to severe erosion, and change was to be promoted over a large area. In this case associated cultivation and management practices which could assist in the control of soil erosion and in the implementation of the new tillage system would also have to be considered, together with the rest of the farming system. The full approach is not generally worthwhile when only isolated farms are to be dealt with. However, even in this case the requirements and implications of any tillage change would still have to be considered in relation to the whole farming system and some components of the FSA approach could still be used.

For the above reasons, and because tillage specialists may frequently be called in to collaborate in a FSA exercise as a member of the multidisciplinary task force, a brief overview of the steps involved in FSA is given below, based on Friedrich (1988):

Prior to initiating a FSA it is important to ensure that the objectives of the study are clearly specified and that they, and the work required to achieve the objectives, are justified by the data presented in the request for the study.

1. **Preparatory arrangements for farm-household and farming systems analysis:**
   - Specification of sites for study, which are determined by the objectives of the study.
   - Collation of background material, such as maps, records, etc.
   - Establishment of a multidisciplinary team, including a farm management economist if possible.

2. **Delineation of farming systems:**
   - The area to be covered by FSA should be divided into homogenous zones with regard to farming systems conditions. These include agro-ecological conditions, such as rainfall, temperature, length of growing period, soil type, topography, altitude, as well as socio-economic conditions, farm size, tenure arrangements, diversity of production, power sources used, etc.

3. **Exploratory diagnosis:**
   - This is an informal data gathering procedure employing direct observations and incorporating these into loosely structured interviews with key informants, groups of farmers, and about 6 randomly selected individual farmers interviewed on their farms. Additional farmers with special characteristics, e.g. model or innovative farmers, may be selected to provide specific information. It is desirable that a checklist of topics is used during the interviews. The purpose of this stage is to gain an understanding of the causal relationships within the farming system and hence to discern the constraints and opportunities. From this information hypotheses are drawn up to explain the present state of development and to define future development opportunities.

4. **Verification:**
   - In most cases the information generated during the exploratory diagnosis stage does not provide a sufficiently reliable base for development planning and policy analysis. A reliable base is required in these cases as they have major consequences for future development, implementation costs, etc. Hence, formal surveys and a quantitative database need to be developed to confirm and quantify aspects of the farming system and to test hypotheses about causal relationships. A quick data collection and analysis exercise is carried out on about 30 farm-households in each identified farming systems zone, and these are usually randomly selected. In addition to these about 6 farmers with special characteristics, e.g. model or innovative farmers, may be selected to provide specific information. These latter purposively selected cases should not be
merged with the 30 randomly selected samples during analysis.

5. Identification of constraints and potentials:
   - These are identified from the general understanding of the causal relationships within the farm-household and farming systems developed through the information gathered in the exploratory diagnosis and the verification survey.
   - Identification of constraints:
     - Establish that a constraint exists in a particular production process:
       - This is often determined by the end result of the completed production process, e.g. a significantly lower yield than possible under local conditions, or annual erosion above acceptable limits, etc. The main constraints are frequently implied in the objectives of the FSA exercise.
     - Determine what the constraint is:
       - This is usually done by looking at all the stages of the production process, again usually starting at the end and working backwards. For example, is the low yield caused by a greater moisture stress than would be expected for the local soil and climatic conditions, and if so does the moisture stress occur at a particular stage of growth, etc.? These aspects are determined by in-field investigations and by studying the current production processes.
     - Determine the causes of the constraint:
       - The causes of the constraint may be obvious once the constraint is identified or it may be caused by the accumulation of the effects of several production processes not suited to the local conditions. A causal chain is usually involved. To assist in this analysis the current production processes are often compared with the optimum ones, or "the best ways of production", appropriate to local soils, climate, and other local conditions. These optimum practices are often embodied in current extension recommendations for the specific area. The analysis then has to move along the causal chain to determine why the optimum production processes are not used. A useful method to assist in this analysis is to draw up diagrammatic representations of the possible causal chains, and this method is elaborated in the next section.
   - Identification of potential solutions and opportunities:
     - Determine potential solutions or opportunities from the understanding built up of the causes or causal chains leading to the constraints.
     - It is important to not only look for the most direct constraints, and solutions to these constraints, but to also look laterally for opportunities that the farmer may not have considered at all. These may range from considering totally new enterprises to reducing the energy and labour inputs into current enterprises so as to reduce costs and open opportunities to undertake new or expanded enterprises.
     - A "constraints tree" may then be formed by combining and simplifying the diagrammatic representations of the causal chains, see Figure ___(@ Friedrich 1988, p 23, fig.3). This is done to draw out the association and hierarchical relationships between the constraints. This allows the constraints to be rated according to their restrictive impact on production and on satisfying the various objectives of the farm-household. From this the importance of overcoming the constraints can be ascertained.

6. Evaluation of potential improvements:
   - From the foregoing the potential improvements to the farm-household system are identified and ranked according to their contribution to the farm-household
goals and objectives. Their impact on the system is then assessed in quantitative terms by comparing the modified farm outputs and inputs. In the first instance this is usually done using gross-margin budgeting or partial budgeting. In case these benefits are substantial, and the solutions seem feasible, then the impact of the potential improvements on the whole farm-household system should be assessed. The main objective is to check on compatibility between enterprises competing for scarce resources and this is generally done by whole-farm budgeting.

- The feasibility of the potential improvements should be considered in the context of their simplicity of adoption; farmer's managerial abilities; risk assessment; sustainability; effects on employment and income distribution; social and cultural acceptance; capability of the farming services organisations to support the improvements through the provision of any required improved inputs; etc.
- The farmers involved in the survey and the whole community should be fully involved in this exercise with the farm systems specialists. This is to ensure that the constraints are properly identified and that the proposed improvements are compatible with the farm-household goals, needs and risk behaviour.

7. Testing:

- On-station testing:
  - The proposed improvements will generally have been selected from optimum practices, or "the best ways of production", appropriate to local soils, climate, and other local conditions. These are often embodied in current extension recommendations for the specific area. These optimum practices will generally have been tested under research station conditions at some earlier stage and will have known effects on soil and water conservation, pest and weed levels, production function values, etc. If this is not the case then they should be tested on-station using standard rigorous statistical procedures. If no research stations are available in the region then researcher managed on-farm trials should be carried out.

- On-farm testing:
  - The proposed improvements should be tested on-farm, under farmer management, in order to ensure that they fit into the local farming systems and are acceptable to the local farm-households and the community. During the testing it may become apparent that the improvements need to be modified or discarded.
  - The testing procedures for on-station and on-farm trials are very different. For the latter emphasis should be placed on testing the technological improvements in a simple manner, under farmer management, over a wide range of farming conditions. The farming systems specialist's part of the exercise should be limited to the provision of the innovation, selection of site, instruction on implementation, checking on accuracy and measurement, data collection, analysis and interpretation.

Friedrich (1988) gives sample checklists of the information to be gathered at all stages of FSA, as well as information on the analysis of the data gathered.

Even when a full FSA approach cannot be justified it is desirable to adhere to its basic framework as closely as time will allow. In these cases the following steps should generally be regarded as the minimum:

- Informal survey.
- Derivation of the causal relationships within the farming system to discern the constraints, the linkages between the constraints, and the opportunities.
- Screening to assess the relevance of potential improvements or opportunities.
Once the Farming Systems Analysis has been completed, including the on-farm testing component, and it has been decided to promote the improvements to the farmers, then it is important to ensure that the farmer service organisations are in a position to support this promotion. Their potential capacity to provide any required support, and the start up time that they would need, would have been established during the process of screening to access the feasibility of the potential improvements or opportunities, i.e. during Stage 6 and possibly Stage 7 above. It must be emphasised that commercial organisations are unlikely to be prepared to make provisions for any potential promotion until guaranteed that the promotion is to be initiated and they have ascertained that the market is commercially viable. This may vary from ensuring that improved implements are available in local stores, which may take years, to training their staff in the safe handling of new pesticides, which may only take weeks, etc.

Only when all the above stages have been completed should the improvements be promoted to the target farming communities, and associated farming sectors or organisations, through standard extension procedures. These procedures are likely to include the following; exhibitions at agricultural shows; on-farm demonstrations; the selection of model farmers to be the first to implement the new systems or improvements; train and visit programmes; etc.

It is also important to emphasise that generally farmers should be cautioned to initially implement new practices on only a small part of their farm. This will enable them to master the management of the new techniques before extending them to the rest of the farm. If this is not done and the improvements do not work due to incorrect implementation, then the farmer's livelihood may be jeopardised and the new techniques and extension organisations brought into disrepute.

8.2. IDENTIFICATION OF CONSTRAINTS IN CROP PRODUCTION

The previous section described the overall approach to take in identifying constraints and opportunities, and the importance in this procedure of building up an understanding of the causal relationships within the farm-household and farming systems. This section will outline the identification of specific constraints in crop production.

A major difficulty in identifying constraints within agricultural production is that production takes place over a long time scale, and the extension worker usually visits the farm for only short periods at specific points within that production process. Hence, the extension worker is likely to miss the signs of a constraint while it is operating, for example, wilting of a crop during moisture stress while crops on neighbouring farms are not wilting. A further complication is that the most common sign that a constraint has been present during a crop production process is stunted growth and this could be caused by several different or interacting factors. It is therefore important that extension workers build up a procedure to assist them in identifying these constraints and their causes. This procedure, described below, is an elaboration of parts of Step 5 of Farm Systems Analysis described in the previous section.

The steps involved in the identification of constraints and their solutions, described in the previous section, are summarised below:

1. Establish that a constraint exists in a production process.
2. Determine what the constraint is.
3. Determine the cause of the constraint.
4. Determine the solution to the constraint.

As described in the section on Farm Systems Analysis it is essential to consider the whole farm-household and farming system when looking for constraints and their causal chains. The full collaboration of the farmer in this process is very important. The main sources
of information for their identification are listed below:

- Farm budgets.
- Field evidence.
- Comparison of outputs, end results and conditions with model neighbouring farmers.
- Comparison with on-station and on-farm research managed trails.
- Condition of equipment used to implement operations.
- Problems observed in the implementation of operations.
- Complaints by the farmer of difficulty in implementing operations.
- Attitude of the farmer to the importance of the various production processes, especially in terms of perceived need, quality and timeliness.
- Resource base of the farm-household and available agricultural service infrastructure.

The following procedure is generally useful in the identification of constraints and their causes in crop production processes:

1. Generally start by comparing the end result of the production process, e.g. total output, with the optimum that could be expected.
2. Identify the key factors which contribute towards the end result of the production process, e.g. for total output it would be area planted and yield.
3. Identify the key stages of development of the crop under consideration.
4. Work backwards from the end result through each of the subdivisions described above and study them for possible constraints and their causes.
5. Consider a constraint occurring during crop germination and growth as being caused by the shortfall between the optimum operation that should have been done at a given stage, for the given environmental and economic situation, and the operation that was done. (Note that a series of operations make up a system, so this step is also considering the whole system).
6. View the sub-optimum operation that was done from the following perspectives:
   - Was the type of operation implemented appropriate?
   - If the type of operation implemented was appropriate, was the implementation of the operation correct, in terms of the following?:
     - Timing of operation?
     - Quality of implementation?
7. Follow the constraints and their causes to the end of the causal chains.

The identification of constraints does not always start at the end of the production process, as direct observations in the field may short-circuit or complement this procedure. Furthermore the analytical procedure involved in discovering the constraints, and the causal chains leading to the constraints, is not strictly a step-by-step procedure because of the large numbers of interacting factors involved. In some ways it is more like constructing a jigsaw puzzle, where components are added as they are discerned and then analysed to see where they fit into the emerging picture.

8.3. SIGNS OF SPECIFIC CONSTRAINTS IN THE FIELD

When looking for signs of constraints in the field there are two main aspects to consider:

1. There may be an intrinsic sign or indicator.
2. The sign may be comparative. An indication that a constraint exists may be observed by comparing a specific factor between two neighbouring farms or fields, which have the same soil and are subject to the same climate but have been cultivated or managed differently.

Signs to indicate possible constraints should be looked for over the whole farm, its layout, management, range and condition of implements, etc., as well as from a detailed knowledge of the local climatic patterns. The growing crop should be studied, both the part above the soil and the root system below the soil. The soil should also be studied, both the
surface condition and to the full depth likely to affect the crop. To do this it is necessary to dig soil pits to study the soil profile and look for the existence of hard and impermeable soil layers, to look for drainage or leaching problems, and to take soil samples. The full collaboration of the farmer in this process is very important. It is also important that the farmer's knowledge and attitudes, misconceptions, etc. regarding operations and processes are taken into account by the extension worker when collecting and sifting through information.

Listed below are some signs, or end results, of constraints and some of their possible causes. These are divided into those relating to the soil and the crop. Figure _____ (@Photographs) is given to assist in the identification process:

A. The Soil:

1. Soil surface:
   - Uncultivated soils:
     - Light-coloured patches of soil or exposed rocks on steeper slopes often indicate sheet erosion.
     - The presence of rills and gulleys indicates rill and gulley erosion.
     - Deposition of soil below slopes usually indicates that water erosion has occurred up-slope.
     - Wind erosion ripples on soil surface indicate existence of wind erosion.
     - Deposition of soil against obstacles may indicate that wind erosion has occurred.
   - Cultivated soils:
     - Erosion of soil around stones or clods on the surface, sometimes leaving them sticking up on small columns of earth, indicates sheet erosion, with raindrop impact being a major factor.
     - The presence of rills indicates sheet and rill erosion.
     - The presence of soil crusts, or knowing that the soil type is prone to crusting, may point to the following problems if not controlled:
       - During seed germination: Poor aeration that can inhibit seed germination.
       - During emergence: Poor emergence.
       - Generally: Poor water infiltration leading to moisture stress.
     - The presence or absence of crop residues should be looked at with regard to their effects on erosion, soil water evaporation, organic matter content, weed and pest problems, etc.
     - The presence of weeds may indicate competition for water and nutrients, and overwintering habitats for pests.

2. Top-soil:
   - Soil texture: The various soil textures have different general characteristics in terms of strength, aggregation, water holding characteristics, fertility, reaction to tillage operations, etc. These broad characteristics should be used to focus the search for various constraints that are more typically found in one texture class than another.
   - Excessively fine tilth: May be caused by excessive tillage or use of inappropriate implements leading to the following constraints or causal chains; low soil organic matter content; poor soil aggregation; low soil pore volume; low infiltration rates; low water holding capacity; low soil strength; possible compaction problems; possible moisture stress; and high soil erodibility.
   - Excessively coarse tilth on soils with high clay content:
     - At seed planting depth: Poor seed/soil contact possibly leading to moisture stress during germination.
     - Top 5 cm: Lack of soil mulch leading possibly to high soil water evaporation losses during long, hot and dry periods and possibly leading to moisture stress.
     - Low soil organic matter content in soil aggregates or soil generally, see Section 2.1.3.5 for field tests. Low soil organic matter levels will lead to poor soil aggregation, low water holding capacity in sandy soils, and associated
problems as described for excessively fine tilth. This is also likely to lead to crop nutrient problems. Possibly caused by excessive tillage or insufficient return of crop residues left as a surface mulch.

- Lower than expected clay content in top layers of sandy soils. Indicated by comparison with neighbouring fields or virgin land, or by concentration of clay in lower layers. This will lead to reduced soil aggregation, higher erosion and poorer nutrient characteristics. Possibly caused by excessive tillage leading to clay disbursement and leaching to sub-soil layers.

- Compacted layers within root-zone, largely impermeable to penetration by water and roots, which may result in the following main constraints:
  - Moisture stress in dry periods, caused by:
    - Reduced rooting depth and volume: Results in the plants having less soil volume from which to draw moisture and nutrients.
    - Reduced water holding capacity: Results from the reduced movement of water to the sub-soil layers and also leads to reduced infiltration, increased runoff and hence increased erosion.
    - Increased evaporation of soil water as it is held nearer to the surface by the hardpan.
  - Waterlogging during wet periods on flat lands, caused by reduced sub-surface drainage.
    - Uniformly compacted topsoil. Similar to above but less marked. Characteristic of soils with poor soil aggregation when not tilled. May be found under zero-till tillage systems, particularly during early stages before the soil organic matter levels have built up.
    - Shallow depth of topsoil may indicate long-term erosion on sloping fields.
    - Bluish-mottled appearance of soil indicates waterlogging in uncultivated soils.

3. Sub-soil:
   - The type of sub-soil, whether clay or gravel, etc., will have a major effect on drainage, and hence on whether moisture stress and waterlogging may be constraints. These constraints may be exacerbated by certain tillage systems.

B. The Crop:
   1. Above-ground:
      - Wilting: Moisture stress occurring during the time of the farm visit.
      - Stunted growth: Poor post-emergent growth caused by wide possible range of factors including; moisture stress; poor nutrition; pests and diseases; or because the crop or crop variety is not appropriate to the local soils or climate. Former reasons relevant to tillage and management systems.
      - Poor stand in terms of low population: Wide possible range of factors including; incorrect planting rate; poorly adjusted planter resulting in large number of misses; poor germination or emergence; pests or diseases.
      - Signs of nutritional deficiencies: There are a number of specific signs of mineral or trace element deficiencies and these are shown in relevant agronomic handbooks. These deficiencies may be related to the placement or leaching of applied fertilizers, which may be related to the tillage system used.
      - Signs of pests and diseases: There are a number of specific signs and these are given in relevant agronomic handbooks. Pests and diseases may be related to tillage in terms of those tillage systems that promote carry-over, e.g. no-till systems or post-harvest operations, or through the control of weeds, or to other cultivation and management systems.

   2. Below-ground:
      - The size and depth of the plant root system is a key indicator of the health and possible constraints operating on the plant:
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- General stunted growth: Wide range of reasons similar to those for stunted above ground growth, as well as general compaction of the soil.
- Growth stunted by compacted layer: Constraints and causal chain as given above. This is an important indicator so a spade should be available. It is important to determine why the layer was formed so that cultivation operations can be modified to prevent it reforming within a few seasons of being broken up.

- Signs of pests and diseases: There are a number of specific signs and these are given in relevant agronomic handbooks. Root pests and diseases may be related to tillage, cultivation and management systems.

C. Weeds and Pests:

1. The presence of weeds and pests during the farm visit, which have reached levels that are, or are likely to be, constraints, may be related to the implementation of various tillage, cultivation or management systems.

Further elaboration of the points summarised above are covered in the rest of this publication and particularly in Section 2. As mentioned previously the causal chains have been followed here for only a few steps, as beyond this stage the path they follow is determined by the particular local conditions. This applies particularly to whether the climate is predominately arid or humid and to the soil texture. The causal chains have not been taken as far as the economic aspects and these are partially covered in Sections 2.5, 5.1, 5.2 and 7. The resource base of the farm-household is crucial in this regard.

8.4. IDENTIFICATION OF OPPORTUNITIES

As emphasised throughout this section, it is important that the constraints and opportunities are analysed within the context of the whole farming system. If this is not done then it is likely that the constraints and opportunities may not be correctly identified. Furthermore, additional opportunities that may exist may not be perceived if alternative enterprises, or a mixture of enterprises, or alternative production processes are not considered.

Once constraints and their causal chains have been correctly identified then possible opportunities need to be determined. These may be self evident or they may involve tackling the constraint in a round-about manner. This may involve altering one or two operations, or of altering the whole production process for that enterprise in order to remove the constraints, or of selecting a different and more appropriate enterprise. In each of the sections in this publication the prime factors involved in tillage have been discussed with the main possible solutions to problems involving these factors also given, usually at the end of each section. An important aspect of these solutions is that some are complementary to each other and some mutually exclusive, or at least with the potential to raise additional constraints. The possible solutions or opportunities then need to be analysed to select the ones most appropriate to the farmer's situation, as discussed in Steps 6 and 7 of Farming Systems Analysis.

The solutions to specific constraints are usually contained in the recommended extension practices or packages for the particular region and category of farmer. However, packages by definition are designed to fulfil the requirements of a hypothetical average farmer in specified regions, and soil types, etc. They may not be fully appropriate to the requirements of a particular farmer in that region, and should then be modified to satisfy the farmer's requirements. Furthermore, extension packages should be continually reviewed to determine whether they are still appropriate in the light of changing conditions and knowledge.

The ways in which tillage, cultivation and management systems can be used to complement each other must always be taken into account when considering opportunities. The use of crop rotations and multiple cropping systems are the basis of viable and sustainable
crop production systems, and frequently determine which tillage systems can be used. These aspects were discussed in Section 3. The objectives of mechanisation, given in Section 5.1 are also an important source of guidance when considering opportunities and these should be referred to.

For all farms, but particularly for small-scale farms, it is particularly important to emphasise that the crop production enterprises should not be dealt with in isolation from the livestock enterprises. There is substantial interaction between these enterprises, with cattle frequently being used as a draught power source and also providing very valuable crop nutrients and soil conditioners in the form of manure. The cattle in turn may be fed crop residues during the dry winter periods, which may preclude the use of crop residues within the tillage system, or alternatively fodder may need to be grown. In many arid and semi-arid areas, not ecologically suited to intensive arable agriculture, the only viable farming systems generally involve a judicious mixture of intensive arable and extensive livestock practices. In these areas it is very important that the stocking rate is kept within ecologically accepted rates and that damage to fragile environments is prevented through the control of grazing.

The importance of not only looking for the obvious constraints and opportunities, but to also think laterally to discern hidden constraints and opportunities, cannot be over emphasised. The main means of doing this is to analyse the objectives of the farm-household and their resource base, and to devise enterprises and production processes that most closely balance these. The work of successful and innovative neighbouring and distant farmers is a key source of inspiration for this. However, it must also be emphasised that change for the sake of change is undesirable. New enterprises and processes always carry the risk of poor initial management, due to the farmer's lack of experience in implementing them, and farmers should not be encouraged to take unacceptable risks with their livelihoods.

Finally, it also needs to be emphasised that the farmers and their community must be intimately involved in the whole process of constraint and opportunity identification. This is a core requirement for the success of the Farming Systems Analysis approach and of agricultural extension work in general.
9. SELECTION OF TILLAGE OPERATIONS AND SYSTEMS

In this section a brief description of a standardised tillage selection procedure will be given, and this will be followed by an overview of how to use the information given in this publication for the selection of tillage operations and systems.

A broad range of knowledge and experience is required to select tillage operations and systems appropriate to a particular set of conditions. This publication provides the core of information required, as well as some guidance on the approaches to take. However, additional knowledge will be required with inputs from specialists in other fields. Due to the broad range of knowledge and experience required it is desirable that tillage specialists in each country provide guidance to general extension workers on the selection of tillage systems in the form of standardised procedures.

9.1. A STANDARDISED TILLAGE SYSTEM SELECTION PROCEDURE

One example of a standardised tillage selection procedure has been developed by Norton (1987). This procedure was specifically developed for cropping in the semi-arid areas of Zimbabwe, but can be adapted for use within other regions and climatic zones. A brief description and discussion of the procedure will be given below.

The procedure was developed to assist extension workers in the selection of tillage systems appropriate to a particular set of conditions. The design of the procedure is such that extension workers without an in-depth knowledge of tillage are able to use it to advise farmers on the selection of tillage systems appropriate to their farms. The procedure is based on following a step-by-step approach, similar to following a flow chart. The starting point is identifying the soil type and its characteristics, then the farmer's resources, climatic zone, and crop type or rotation. Generally, each of these characteristics is quantified into 2 to 4 ratings. The characteristics used in each category are listed below:

1. Soil type:
   - Topsoil (less than 250 mm depth) - Texture - 3 ratings.
   - Subsoil - Drainage/permeability - 3 ratings.
   - Wetness/hydromorphic characteristics - 4 ratings.
   - Capping characteristics - 3 ratings.
   - Erodibility rating - 3 ratings. Based on observed erosion, surface soil condition (capping), effective soil depth, and slope.

2. Farmer's resources:
   - Draught animal teams available - 3 ratings.
   - Labour available - 2 ratings.
   - Equipment available - 4 ratings.

3. Climate:
   - Based on agro-ecological zones - 3 ratings.

4. Crop type or rotation:
   - Suitability of crop and rotation to specific tillage systems.

For each of the four main categories above the user follows a flow chart, which covers all possible combinations of the characteristics, and selects the various ratings of characteristics that apply to the particular situation. At the end of the line a list of tillage systems is given which could be used for that particular combination of characteristics. These are then listed on a chart of the four categories. A tillage system is then chosen which satisfies the requirements of all four categories. This is the tillage system appropriate to all the requirements of the particular situation.

The tillage systems used in the procedure are similar to those listed in Section 3.
reasonable understanding of all the parameters used in the flow chart is required to use this procedure, and non-specialist agricultural extension workers who have covered basic courses such as Land Use Planning generally have this knowledge.

This standardised selection procedure has not been expanded to be universally applicable. This is probably not worthwhile, due to the increased complexity of having to deal with the full range of climate, soil and crop types, and all the tillage, cultivation and management systems. However, the procedure can be adapted by local tillage specialists to regions in which there is not too great a variation in the climate, soil and crop types and in the cultivation and management systems used.

Several important points relating to the use of a standardised procedure are made below:

- Most of the characteristics used to select tillage systems interact and this frequently makes the selection of appropriate tillage systems difficult, even for experienced extension workers. It is therefore desirable for tillage specialists in each country to adapt the procedure developed by Norton (1987), or to devise a similar one, for use within their country.
- An advantage of the procedure is that it can be used by extension workers who do not have an in-depth knowledge of tillage. However, due to the fundamental importance of tillage for sustainable crop production, it is important that this is not seen as a justification that an in-depth training in tillage is not required. An in-depth knowledge of tillage is required for work involving the identification of constraints and opportunities relating to tillage, and this is of fundamental importance to extension workers practising in the crop production field.
- The procedure developed by Norton (1987) does not list or explain why certain tillage systems are inappropriate to certain sets of conditions. It would be desirable to expand the procedure to include this information, when it is being adapted to other countries, as it would then also fulfil a more educative function each time it is used.
- The rating of the characteristics is done on a fairly rough basis, but it is essential that the characteristics are rated and refinements can be added as they are developed.
- The procedure is only as good as the information on which it is based.
- In some regions there may be only a couple of tillage systems that are suitable and a sophisticated selection procedure may not be required.
- It is unlikely that any procedure can take into account all eventualities and so the end result should always be questioned by considering alternatives, or looking at the situation from a different angle.

9.2. THE USE OF THIS PUBLICATION IN THE SELECTION OF TILLAGE OPERATIONS AND SYSTEMS

The order in which the information has been presented in this publication has been largely determined by the need to first introduce those factors of which knowledge is required in order to describe other components of a tillage system. The order used does not generally facilitate its use in the selection of tillage operations and systems appropriate to a particular set of circumstances. Hence, a brief description of how to use this publication for this purpose is given in this section. This has been partly covered in the previous section on the identification of constraints and opportunities and in the description of a standardised selection procedure above. This final section is also in effect an extremely brief summary of the majority of the information given in this publication.

Each of the sections has generally followed a basic format by discussing, in order, the relative importance of the aspect of tillage being covered, its characteristics, how it interacts with other components of tillage and other crop cultivation and management aspects, and lastly how it can be controlled to provide the desired characteristics. All of these aspects are
important in the selection of tillage operations and systems.

Tillage operations are selected to achieve a specific effect, usually the control of a specific factor, and these were discussed in Section 2, generally towards the end of each section. The objectives and implementation of individual tillage operations are listed in Section 5.3.

Tillage systems are made up of a specific series of tillage operations, which combine the effects of the individual operations to achieve an overall objective. Tillage systems can be selected by two main methods:

1. Through the study of the properties of standard tillage systems and the selection of the one that most closely meets the required objectives.
   - Section 3.1 in which the implementation and properties of the various categories of tillage systems are given, is the main section to use for this method.

2. The tillage system can be built up by the selection of sequential tillage operations to meet the required objectives.
   - Section 2 in which each factor and its control by tillage is discussed is the main section to use for this method.

For both methods the information given in the rest of this publication provides supportive information. This particularly applies to Section 3.2 that covers the cultivation and management systems of which the tillage system is a component. It is essential for sustainable crop production that the tillage system chosen is complementary to suitable cultivation and management systems. Section 5 is used to obtain further details of the tillage operations and to select the implements that provide the tillage properties required.

For both methods of selecting tillage systems the first step in the process is to determine the required tillage objectives. These objectives are specific to the conditions pertaining to a particular site and farmer.

The climate is usually the most important factor, and the first one to be considered, as it determines the amount and distribution of precipitation, evaporation potential, temperature, season length, etc. The tillage objectives in the major climatic zones were given in Section 2.3.2. The tillage objectives in the main climatic zones should be seen as the minimum to be considered, and additional requirements, limitations, etc., relating to the particular conditions of the farm and farmer should be added. These include the desired objectives relating to the soils, soil erosion, agronomic factors, economic factors, and other cultivation and management requirements. The objectives of the farm-household, their resource base and the risk strategies that are acceptable to them, are important in this regard and were discussed in Section 2.5. When starting the process of selecting tillage operations and systems it is important that these objectives are first written down clearly before proceeding.

An important advantage of the first method listed above is that standard tillage systems commonly used in a country are by definition generally well known to extension staff and farmers. This means that they understand how to implement them and are familiar with the risks involved. However, if there are serious deficiencies in these tillage and cultivation systems then there are numerous alternative steps or systems that can be used to overcome these deficiencies as outlined in this publication. In line with this the less the standard tillage system is altered the more likely it is to be widely adopted by farmers. However, if the disadvantages of the current system are significant and the advantages of a new system great, then perhaps new tillage and cultivation systems should be promoted following significant programmes to test the systems locally and to ensure that they fit in with the resource bases and risk capacities of the farmers. These would then need to be followed up by full extension
procedures.

Based on the second method outlined above the key factors are very briefly summarised below together with some of the main tillage objectives and operations used to achieve them. Some of those tillage operations and systems that should be avoided for particular conditions are also given. The selection procedure involves listing both the desired and undesired tillage operations in order to focus on the ideal one. It is very important that the summary given below is seen as only a skeleton to give some form to the selection procedure, as it is in effect a summary of this whole publication. Extension workers should supplement the information and steps in this procedure as they work through this publication and obtain information from other sources.

From Number 2 below onwards, the nested format is generally based on the following sequence:
- The overall factor or category that is to be controlled by tillage is initially stated
- The specific factor is then stated
- The objective of the tillage operation to achieve the above is then given
- The tillage operations required to achieve the above objective are then listed

1. Climate:
   . Precipitation - amount, distribution and reliability through year.
   . Evaporation potential - level and variation through year - net water balance.
   . Temperature - level and variation through year.
   . Length of growing season - based on temperature and precipitation.
     - The tillage objectives for the major climatic zones were given in Section 2.3.2 and these objectives are outlined below and then extended with further considerations.

2. Soil water:
   . Infiltration:
     - Where precipitation is deficient then maximise total infiltration:
       . Maximise infiltration rate:
         - Minimise capping on clay and loam soils:
           . Retain crop residues on the surface.
           . Minimise pulverisation of soil by avoiding intensive tillage operations, (Section 5.3.). Use reduced or zero-till systems where possible.
           . Strengthen soil aggregates:
             - Increase soil organic matter content, (Section 2.1.3.5.).
             - Shallow till to break up capping after each rainfall event on capping soils where no crop residues retained on surface.
         - Maximise soil pore volume:
           . On well-structured soils:
             - Maintain good soil aggregation by maintaining good soil organic matter levels, (Section 2.1.3.5.), and avoiding tillage operations which pulverise the soil, (Section 5.3.). Use reduced or zero-till systems where possible, (Section 3.1.).
             - Fracture soils with chiselling or ripping operations to open up channels to lower layers. But balance against loss of soil organic matter due to tillage, (Section 2.1.2.3.).
           . On poorly-structured soils:
             - On sandy soils tillage leads to clay disbursement
and subsequent leaching of clay particles, resulting in reduced soil pore volume and strength. But tillage may be required to obtain reasonable rooting volume.

- Increase soil aggregation by increasing soil organic matter content, (Section 2.1.3.5.).
- Minimise compaction due to traffic over surface, (Section 2.1.2.7.).
- Fracture soils with chiselling or ripping operations in plant row and avoid re-compaction by selecting strip-tillage systems, (Section 2.1.2.3/7.). Where possible combine with periods of zero-till, (Section 3.1.).

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Retain water on surface to lengthen time available for infiltration:
- Increase surface roughness:
  - Retain crop residues on surface.
  - Select tillage systems that leave large clods on surface.
- Form small water retaining structures on the surface:
  - Till on-contour or slightly off-contour, (Section 5.3.4.).
  - Use tied-ridging tillage systems, (Section 3.1.).
  - Use pot-holing tillage operation, (Section 3.1.).

Where precipitation is excessive:
-Even in arid areas precipitation is often excessive at times and any runoff should be controlled, see erosion below.
-Where precipitation is excessive for sufficiently long periods to cause severe waterlogging problems then controlled surface drainage should be included in the tillage system:
  - Avoid zero-tillage systems and retention of crop residues on surface as these hold water on the surface.
  - Use ridging tillage systems with ridges slightly off-contour. This controls the speed of runoff, which is particularly important when the surface is not protected by crop residues. Seed zone in ridge top does not suffer from water-logging.
- Promote soil aggregation to improve internal drainage:
  - Incorporate crop residues to maintain soil organic matter levels, (Section 2.1.3.5.).

Evaporation:
- Where evaporation is high, and particularly in precipitation deficient areas, then minimise evaporation:
  - Retain crop residues on surface to reduce heat flow into soil. This is particularly effective for short hot dry periods of high evaporative potential.
  - Break capillary continuity between surface and lower levels to reduce water and water vapour flow to surface by creating shallow soil mulch on surface. This also reduces heat flow to lower layers. This is the most effective control for long hot dry periods of high evaporative potential, and especially as a post harvest operation. Also used in clean tillage fallow systems.
  - In areas of low rainfall shallow tilling the topsoil to just below planting depth to create increased pore volume to increase water holding capacity of soil can also result in all the rainfall being retained near the surface from where it is easily evaporated. Preferable to use strip tillage and fracture soil in plant rows to open up channels to lower layers for deeper storage of water.
  - Avoid or minimise use of inversion tillage operations as these bring moist soil to the surface resulting in increased moisture loss.
Note that timing and depth of tillage and the tilth created to control evaporation all have important effects on the level of control.
See Section 2.1.2.4 for all of the above.

Drainage:
- With only a few exceptions it is desirable to promote good drainage for all climate and soil types. In areas of high rainfall, or during high rainfall periods in semi-arid areas, this will reduce water-logglogging problems. In areas of low rainfall this will transport water to the lower soil layers where it is less prone to evaporation.
  - Promote drainage by increasing the soil pore volume, see above.
  - Where impermeable hardpans occur break these with subsoiling operations.
- On sandy soils with good drainage tillage can lead to clay disbursement and subsequent leaching of clay particles, so minimise tillage.
- Excessive drainage also leads to the leaching of fertilizers, so possibly use ridging tillage system as main drainage route is below fertilizer placement zone (Section 3.1.2.3.), or use periodic placement of portions of total fertilizer application.
- In areas of low rainfall with shallow soils and highly permeable substrates, e.g. gravel, do not promote drainage through tillage operations.
- Where drainage is poor and soils are prone to waterlogging then generally do not retain crop residues on the soil surface as this will promote waterlogging. Generally crop on off-contour ridges where the seed zone will not be prone to waterlogging and excess water will be taken off the field at non-erosive speeds.

Water-holding capacity:
- It is particularly important to maximise water-holding capacity in arid and semi-arid areas, but this is also desirable in most areas to avoid the problem of short-term droughts:
  - Water holding capacity is maximised by maximising soil pore volume by increasing aggregation:
    - Maximise organic matter levels:
      - In arid areas retain crop residues on surface and minimise tillage, i.e. use zero or reduced-tillage systems.
      - In areas prone to water-logging incorporate crop residues.
    - In sandy soils soil organic matter is an important water holding medium in itself, (Section 2.1.3.2.).
    - Other than in zero-tillage systems fracture soil to produce channels to hold water and transport it to lower soil layers.

3. Erosion potential:
3.1. Where there is a potential of erosion due to water tackle the problem by considering each of the main factors involved in water erosion:
   - Reduce detachment of soil particles from surface aggregates:
     - Use soil cover to protect soil from raindrop impact:
       - Increase crop cover during periods of high erosive potential through selection of crop type, or appropriate cultivation or management systems.
       - Retain crop residues on surface through selection of appropriate tillage systems.
     - Increase binding strength of soil particles to aggregates by increasing soil organic matter content.
   - Increase infiltration rate:
     - Increase amounts of crop residues on surface.
     - Increase degree of soil aggregation.
     - Reduce bulk density.
- Increase degree of fracturing.
- Increase length of time that infiltration rate remains high:
  - Increase proportion of water-stable aggregates.
  - Increase depth of tillage and ensure no impermeable layers.
- Increase length of time that water can be held where it falls on the soil surface to increase length of time for infiltration to take place:
  - Increase surface roughness through increasing cloddiness or retention of crop residues on the surface.
  - Implement all tillage and planting operations on-contour or slightly off-contour.
  - Use tied-ridging or pot-holing tillage operations.
- Reduce the speed of runoff:
  - Use tillage operations such as ridging slightly off-contour.
  - Use strip-cropping systems to provide obstacles to flow, (Section 3.2.).
  - Use mechanical conservation works, e.g. construction of contour ridges, waterways, terracing, etc., to reduce the down slope length of the field or reduce the steepness of slope, (Section 4.).
- Where an average erosion potential exists generally avoid tillage systems that involve strip or shallow tillage when these are combined with no retention of crop residues on the surface.
- Where a high erosion potential exists generally limit tillage systems to only those that retain adequate crop residue cover. Otherwise use ridging system on suitable lands. Furthermore, combine these with suitable multiple cropping systems.
  - See Section 2.2.1.3. for all of above.

3.2. Where there is a potential of erosion due to wind tackle the problem by considering each of the main factors involved in wind erosion:
- Increase surface soil aggregation to reduce the susceptibility of particles and aggregates to being transported:
  - Increase soil organic matter content.
  - Minimise tillage operations and avoid those that excessively fragment soil structure.
  - Raise aggregates to the surface and bury finer particles.
  - Protect soil surface from raindrop impact:
    - Retain crop residues on surface.
    - Increase crop cover.
- Increase soil moisture content to reduce the susceptibility of particles and aggregates to being transported:
  - Increase water infiltration.
  - Reduce water runoff.
  - Reduce soil water evaporation.
- Increase surface roughness to trap particles and aggregates once they have started to move:
  - Increase cloddiness and ridge roughness.
  - Retain crop residues on the soil surface.
- Reduce surface wind speed to reduce its capacity to transport particles and aggregates:
  - Increase surface roughness.
  - Increase in-field wind barriers:
    - Increase growing crop cover.
    - Retain standing crop residues.
  - Increase out-of-field wind barriers:
    - Provide suitable wind breaks.
    - Reduce length of field below wind breaks to suitable length.
  - See Section 2.2.2.3. for all of above.

4. Soil organic matter:
Maintain or increase soil organic matter levels through:
Regular addition of organic carbon and nitrogen to soil:
- Retention of crop residues on the land.
- Addition of organic wastes.
- Use of green manures.

Addition of nitrogen and other plant nutrients:
- Inclusion of legumes in the rotation.
- Use of mineral fertilizers to minimise constraints to crop production and hence vegetative production.

Establish acceptable pH levels:
- Use of minerals and manures to attain correct pH levels.

Reduce tillage operations, to reduce decomposition of soil organic matter:
- Use of zero-till systems with the retention of crop residues to protect soil surface, reduce water runoff and increase infiltration.
- Use of reduced tillage operations with partial incorporation of crop residues to protect soil surface.

Improve water balance:
- Reduce runoff and improve infiltration, through retention of crop residues on surface, and/or appropriate tillage systems, e.g. tied-ridging, pot-holing, chisel ploughing to increase infiltration, etc.
- Reduce soil water evaporation, through retention of crop residues on surface, or shallow tillage to break capillary action.
- Use of supplementary irrigation.
- Use of fallow periods.

Reduce soil temperature in high temperature regions:
- Retention of crop residues on surface.

Take land out of cultivation that is not suitable for cultivation.

See Section 2.1.3.5 for all of above.

5. Soil texture and structure:
5.1. General tillage objectives for various soil texture classes and some characteristics of these classes:

Clay, silt clay, sandy clay, silt clay loam, clay loam:
- Protect soil surface from capping, see below.
- On these classes of soils prone to waterlogging:
  - Promote good drainage.
  - Avoid use of residues if waterlogging is a problem.
- Timing of operations important. Soils highly compactable when moist and hard when dry, which reduces time available for tillage operations.
- Production of correct tilth, i.e. correct soil aggregate size, through appropriate tillage operations is important for good seed/soil contact for good germination.
- These soils have good water holding characteristics when their structure is good.
- These soils generally have good fertility characteristics.
- When these soils are in poor condition, i.e. poor structure and low soil organic matter levels, the clods and soil aggregates will collapse into a dense mass with onset of rains, leading to low infiltration, high runoff, and erosion losses of soil and nutrients. Soil will be difficult to plough, giving rise to very large hard clods and will require several secondary tillage operations to form a fine tilth.

Sandy clay loam, loam, sandy loam, silt loam, loamy sand:
- Characteristics in between those of clays and sands.

Sand, silt:
- Prone to wind erosion due to small size of soil particles and lack of cohesion between them.
- Less compactable than clays when moist, compactable when dry.
- On sandy soils tillage leads to clay disbursement and subsequent leaching of clay particles, resulting in reduced soil aggregation, soil pore volume, strength,
water holding capacity and also poorer nutrient characteristics in the tilled layer. This is particularly pronounced with good drainage. But tillage may be required to obtain reasonable rooting volume, particularly in arid and semi-arid areas.

- Fertility depends to a very large extent on the amount of organic matter present, not in so much in terms of producing water stable clods, but by improving the structure through spacing out the soil particles, and by the properties of the soil organic matter itself. Sandy soils in good condition will lead to high infiltration, low runoff, low erosion losses of soil and nutrients, and will be able to hold more nutrients and transfer them more efficiently to the plants.

See Section 2.1.3.4 for some of the above.

5.2. Rectification of compaction problems:

- **Hard surface crusts or capping:**
  - Maintain a moist soil surface during germination and emergence to reduce the strength of the surface layer.
  - Retain residue mulches on the surface to reduce capping caused by raindrop impact, and to maintain moist surface by reducing drying.
  - Shallow tillage to promote water infiltration and improve aeration and, prior to emergence, to allow emergence of the petioles.

- **Plough pans or hard impermeable layers at depth:**
  - Fields should always be checked for the existence of plough pans before planning tillage operations. If they exist then they should be either deep ploughed or ripped, depending on depth. In subsequent ploughing operations the depth of ploughing should be alternated to reduce likelihood of their formation.
  - Deep rooting crops with strongly penetrating root systems can sometimes be used in a rotation to break through hard impermeable layers.

- **General compaction:**
  - Deep plough or rip to reduce soil strength. Identify source of compaction for future avoidance due to cost of rectification.
  - Increase organic matter content so as to increase aggregation as well as the strength of the aggregates when moist.

- **Once compaction problems have been rectified ensure that subsequent operations minimise the likelihood of their reoccurrence.**

- See Section 2.1.2.7 for above.

6. Seed germination and emergence:

- **Good seed/soil contact is important to facilitate the imbibing of water by the seed from the soil:**
  - Soil aggregates in the seed zone should generally be tilled to 1 to 5 mm in size, with small seeds requiring a finer tilth than larger seeds.
  - Problems with poor seed/soil contact most commonly occur on clay soils that become cloddy when tilled or planted. These clods should be broken down to the required size in the seed zone.

- **Seed zone should be in capillary continuity with subsoil water:**
  - Seedbed may need to be rolled to compact it to achieve this and to produce a finer tilth for improved seed/soil contact.
  - Planting may need to be delayed to build up capillary continuity with subsoil water, especially when planting on the ridge.
  - Use evaporation control measures in water deficient areas, especially in post harvest operations, to conserve water and promote water continuity between seed zone and subsoil layers.

- **Tillage systems in which crop residues are retained on the surface require special considerations:**
  - For mechanised planting specialised equipment may be required.
  - Improved pest control measures are required.

- **Soils prone to capping should be treated as described in 5.2 above.**
7. Nutrient requirements:
   - Select tillage operations and systems that minimise loss of nutrients and added fertilizers by erosion, leaching or loss to atmosphere:
     - Minimise erosion, as described previously.
     - Nutrient and fertilizer particles are either held in the soil by clay particles and soil organic matter or are unattached. When water drains through the soil it dissolves and carries the unattached particles with it to soil layers below the maximum rooting depth of the crop. Therefore minimise leaching by:
       - Promoting good soil organic matter levels as, described previously.
       - On sandy soils minimise tillage to minimise the disbursement and leaching of clay particles.
     - Possibly use ridging tillage system as main drainage route is then below fertilizer placement zone (Section 3.1.2.3.),
     - Use periodic placement of portions of total fertilizer application where leaching is excessive.
     - Control the loss of nitrogenous components to the atmosphere by pacing fertilizer and manures within soil, or leave on surface for as short a time as possible.
   - Select tillage operations and systems that maximise the use of nutrients in crop residues:
     - Incorporate crop residues in clean tillage systems or retain them on the surface in zero-till or stubble mulch systems.
     - Tillage systems in which crop residues are incorporated annually generally require lower levels of additional fertilizer than zero-till systems, as the rapidly decomposing organic matter in the former system releases greater amounts of nutrients. However, this is a complex area, see Section 2.1.3.4 and 2.4.1.3 for further details.

8. Weeds:
   - The efficient control of weeds is crucial to most crops in most regions and requires good management planning by the farmer, (Section 2.4.2.).
   - Inversion ploughing is usually the most efficient way of controlling a severe weed problem.
   - The mechanised control of weeds is difficult in zero-till or stubble mulch systems. Unless manual implements are used herbicides are generally required, which may limit the use of these tillage systems.
   - The use of multiple cropping systems and especially crop rotations are very important in the control of weed problems, especially in zero-till systems and when herbicides are being used, (Section 3.2.).

9. Pests and diseases:
   - The efficient control of pests and diseases is crucial and requires good management planning by the farmer, (Section 2.4.3.).
   - Tillage systems in which crop residues are retained on the surface, and especially zero-till systems, can lead to severe pest and disease problems, due primarily to carry-over of pests and diseases from one season to another. They require substantial management ability on the part of the farmer to control them, as well as access to pesticides, which may limit the use of these tillage systems. However, it should be noted that there are several simple methods to control specific pests that minimise the requirement for chemicals.
   - The control of weeds is an important aspect of the control of pests and diseases, as they provide a habitat and food source for them. This applies particularly to the carry-over from one season to another. Post harvest control of weeds is therefore important.
   - The use of multiple cropping systems and especially crop rotations are particularly
important in the control of pests and diseases, (Section 3.2.).

   . The growth habit and means of harvesting sometimes limit the types of tillage systems that can be used: Mechanised harvesting of cotton sometimes requires that residues are not retained on the surface. The planting of crops with a low habit on ridges can facilitate mechanised harvesting, especially as debris tend to fall into the furrows and so facilitate a clean harvest, e.g. cotton. Harvesting of groundnuts is facilitated by planting on ridges or in beds, etc.

11. Labour and energy inputs and power requirements.
   . Labour and energy inputs and power requirements are important considerations in the selection of tillage operations and systems. Reduced and zero-till systems have important advantages in this regard, (Sections 3.1., 5.2., 5.3. and 7.).

12. Equipment requirements:
   . Some tillage operations require specialised equipment, although standard implements can frequently be adapted to implement them. The sourcing, availability, servicing and cost of implements are all important considerations, (Sections 3.1., 5., 6., and 7.).

13. Management requirements.
   . The management requirements of the various tillage operations and systems is one of the most important considerations in the selection of appropriate tillage operations and systems. The ability to implement the tillage operation under the correct conditions is of basic importance, (Section 5.3.). The aspect requiring greatest management ability is the control of weeds, pests and diseases, all of which are largely affected by the tillage system chosen. Zero-till systems in particular require a high management input. See Sections 3.1. and 2.4.2/3/4.

14. Economic characteristics:
   . The prime economic considerations are profitability and risk, (Section 2.5.):
     - Profitability: This is determined primarily by the input costs of the whole production system and the sustainable yield. The tillage system used will also partially determine the fertilizer costs and weed and pest control costs and these are important considerations. For subsistence farmers the input costs are primarily labour inputs.
     - Risk: The risk of the tillage system used in terms of its sustainability, ability to withstand short-term droughts, influence on weed and pest infestations, etc. is an important consideration.

For most fairly homogeneous regions there are usually one or two overriding factors that largely determine which tillage systems should or should not be used. Hence, although the above procedure is initially lengthy and detailed, extension workers will rapidly build up an in-depth knowledge of tillage operations and systems suited to their local areas and to the particular requirements of different groups of farmers.
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