Statements

1. In the tropical area of Mexico, the range of moisture contents allowing to reach the optimum technological result from conventional tillage is narrow. Failure to work within this range is the cause of most problems related to tillage in the area.
   – *this thesis*

2. Soil moisture content is the key factor determining both the technological result from tillage and the energy required to carry out tillage operations.
   – *this thesis*
   "Initial moisture content of the soil is the single factor largely influencing the effect of a tillage operation." (Spoor, 1977).

3. The selection of a tillage system must be based on the knowledge of the workable range of a soil and of the workable periods resulting from the interaction between soil and weather factors. The workable range of a soil can be found with simple laboratory tests.
   – *this thesis*

4. An adequate representation of the distribution of water in the soil profile can be obtained by deterministic simulation models. This is very useful for the analysis of tillage systems in their ability to reach a timely preparation of land for crop establishment.
   – *this thesis*

5. Farmers using animal traction for tillage always carry out the operations in the optimum soil workable condition, simply because they are forced to do so as a result of the low level of available power.
   – *this thesis*

6. A decision support system using a.o. workability information from laboratory tests, completed with site-specific information as provided by the user (farmer, extension officers), is able to supply correct and unbiased recommendations on tillage systems.
   – *this thesis*
   "There is need, not only to find research solutions to production-management problems facing farmers, but to make the technology transfer readily available to them." (Mannering et al., 1988).

7. Technology should be at the service of everyone, not only at the service of those who can afford it.

8. It is not possible to stop the degradation of natural resources in developing countries if policies for land use are oriented to obtain short-term profits.

9. We should share our wealth and teach our children to do likewise. This will contribute greatly to global development. It is a shame that on the one hand mankind launches spacecrafts and on the other hand people are starving.

10. Communication technology is highly developed making the world seemingly smaller. Yet this does not help solving communication problems between two people or within a family.

'Soil workability as a basis for advice on tillage activities'

Martin Cadena Zapata, Wageningen, 15 June 1999

SOIL WORKABILITY AS A BASIS FOR ADVICE ON TILLAGE ACTIVITIES

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SOIL WORKABILITY AS A BASIS FOR ADVICE ON TILLAGE ACTIVITIES

Martin Cadena Zapata

Proefschrift

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COVER PHOTO: detail of a painting from the state of Guerrero, Mexico. Author anonimus. Traditionally, native people use to paint on bark paper (*papel amate*) scenes of the community life, landscapes and wildlife in bright colours with natural pigments. The detail shows the crop establishment by tilling the soil with wooden plough and sowing by hand.

To María de los Angeles and our beloved children

ABSTRACT

Cadena Zapata, M., 1999. Soil workability as a basis for advice on tillage activities: A case study in the tropical area of Mexico: Veracruz. PhD thesis, Wageningen University, the Netherlands, (144 pp.). With ref. - With summary in Spanish and Dutch, ISBN 90-5808-077-3.

Key words: Soil workability, specific energy for tillage, tillage results, water balance, expert systems

The workable range of soils in the tropical area of Mexico was quantified by measuring in-field implement effects and the specific energy applied, both in a range of moisture contents inside and outside the theoretical friable consistency of the soils, determined by the shrinkage and plastic limits.

Empirical relationships between initial moisture content and the technological result of tillage showed that results from loam and clay soils, changed from optimum to sub-optimum at soil water potentials that rather coincide with the plastic limit in relatively moist soil. As soil was drying out, the implement effect changes from optimum to sub-optimum at soil water potentials well above moisture content at the shrinkage limit, so the actual field workable range was smaller than the theoretical friable status of the soils. The minimum input of specific energy to obtain optimum results, was close to the soil water potential where results changed to sub-optimum as soils were drying out. Observations in a sandy soil indicates that required technological result can be attained at almost any moisture content

Laboratory tests were implemented to represent a wet workability limit and a dry workability limit which could represent change in the optimum and sub-optimum results from the field experiments for the loam and clay soils. The thresholds established by the results from both tests agree well with the findings in the field, so workability limits in terms of soil water potential can be established for other soils in the area by means of the laboratory tests used here.

For tillage planning, valuable information on workable periods can be obtained by making use of a detailed water balance and quantified workability thresholds. As limited soil data is available in the tropics of Mexico, the possibility of estimating soil hydraulic properties by using PTF's, for use in a deterministic water balance model, was explored.

Workability based decisions for tillage planning and operation can be made by calculating workable periods and then analyzing them together with crop and environmental information, as well as power and implements availability. A proposition of an automated analysis system (in an early stage) is presented, from which information can be derived to support decisions on tillage activities, given available specific data.

CONTENTS

PREFACE

The technology for crop production includes the means of work (among others the implements and machines) and the objects of work (among them the soil manipulation). The components of technology for crop production, have been generated either empirically or scientifically for specific conditions. In the tropical area of Mexico there is evidence since pre-hispanic times (before 16th Century) that the tillage systems, a component of crop production technology, were based in empirical knowledge notably adapted to the preservation of soil. In this area of the country the common practice was slashing and burning, then establishing the crop (sowing by wood stick and weeding by hand) for one or two consecutive years, and finally left fallow for 16 to 25 years to restore fertility by regeneration of native vegetation. This system had left unprotected the soil for very brief periods, so the erosive effects of the intense rainfall of the region were minimal. In present times it is not possible to practice this system since the same piece of land has to be worked every year. The introduction of the mouldboard plough by the Europeans (after 18th Century) gave a more intensive tillage system, although most of the crop production was established in the temperate area of the country. Later on, the introduction of tractors in this Century, increased dramatically the area of crop production as well as the intensity of soil manipulation. The intensive agriculture, until 30 years ago, was still in the country in the temperate and semiarid (in irrigation schemes) areas. Since then, thousands of ha in the tropical area have been cleared every year for agricultural use. Indiscriminate use of tillage practices from the technology for crop production in the temperate areas has been introduced in the tropics and, because of different environmental conditions, the use of those practices has lead to the deterioration of the natural resources, specially of the soils. here is a lack of knowledge about which tillage systems would be the best to use, and when and how operations should be carried out to avoid the deterioration of natural resources in the tropical environment.
The research in this thesis aims to contribute with some of the information required for a proper management of the tillage practices in the tropical area of Mexico. The work is part of the multidisciplinary research carried out by The National Institute of Forestry, Agricultural and Livestock Research (INIFAP) to generate the technology for crop production in this region of the country, and to try to avoid the deterioration of natural resources.

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1 INTRODUCTION

1.1 Background

Soil tillage is a basic component of agricultural production technology. It is involved in the production of all crops. The choice of tillage method depends on several factors including soil, climate, crops grown and prevailing financial and societal conditions. These factors dictate the specific objectives and nature of tillage operations. Though there must be an awareness of local conditions when choosing a soil management system, in many places the development of cultivation practices is still supported and or generated by trial and error over many years (Hadas et al., 1988).

This is also the case in the tropical area of Mexico, where intensive cultivation began around 1970 when agricultural machinery was more widely introduced. Before this most of the agricultural production was located in the temperate and semiarid part of the country. Soil management techniques were transferred and used whenever possible, in spite of great differences in soils and climate. Because of inadequate current soil management, there are soil erosion and compaction problems in many agricultural lands in the tropics of Mexico (Cornish et al., 1986). Assessments in central Veracruz State show that the arable layer has often been lost. There is a consequent decline in crop yields which have fallen to less than half compared with those 20 years ago (Uresti and Cadena, 1992). Power and tool selection is made qualitatively. There is not quantified information about the interaction between a chosen process of cultivation, soil type and weather, which dictate the draught and power requirements (Moreno et al., 1993). When and how to carry out tillage is a qualitative decision, often resulting in excessive and unnecessary work, waste of energy, delay of operations, soil exposure to water erosion and structural damage. This also occurs outside the tropical area of the country. In Mexico, 11.4 million of ha are managed by tractors, and during seedbed preparation, tillage is very commonly carried out in a dry consistence of soil, requiring at least two passes of the disc plough and more than two passes of the disc harrow to get an acceptable seedbed (Pineda et al.,1996). On the other hand conservation practices such as no tillage and minimum tillage have failed in many places, and improper variants of these systems are used according to soil types and crops. There is a lack of information necessary for the planning and operation of tillage options which could otherwise achieve the timeliness required (Moreno et al., 1993).

Schafer et al. (1985) state that "tillage began to change from an art to a science when man attempted to describe and quantify the soil conditions that improved plant growth". Hillel (1980) points out that the precise effects of tillage on soil structure must be defined and optimized in each case, if tillage is to be transformed from a "hit or miss art" to a scientifically based, dependable, and sustainable means of production. Indeed it is now possible to take advantage of existing knowledge of the functional needs of crop production. This includes knowledge of the physical environment needed by the plants, for soil and water conservation and for mechanization. When combined with the modes of tool operation, this knowledge can enable effective scheduling of farming operations and improvements in soil management.

Climate and soil characteristics determine the initial physical condition of the soil at any specific location. It is possible to modify, change or improve to other required soil structures by means of tillage, but care must be taken as to when to carry out the tillage operations. Among the physical properties which determine the nature of soil reaction to a tillage tool, soil moisture is the most important (Hillel, 1980). Moisture can cause the soil to vary from a hard condition to a plastic one. The same implement or tillage treatment will produce different soil environments, depending in particular on the soil consistency (Spoor, 1975). In the tropical area of Mexico a different approach from that currently used for soil tillage management is necessary. Objective criteria should be used for selecting when and how to do cultivation in order to meet the crop and conservation requirements. During the decade 1980-1990, crop land in the tropical zone expanded from 4 million to approximately 8 million ha, and now represents more than one quarter of the total agricultural area of the country (INEGI, 1992). It is now recognized among the agricultural sector that it is imperative to set up adequate tillage management and conservation measures (SARH, 1992). Agricultural sustainability is urgently needed, particularly in several tropical eco-regions. Future tillage systems must enhance agricultural productivity while conserving resources and using energy most efficiently (Lal, 1991). In practice, the farmer is limited in his choice of tillage operations, to the level of available technology and to his economic and social environment. However, a major role of science is to increase the possibilities to choose from, by explaining technical relations. From each given climate-soil-crop system, a suitable soil tillage system could be derived (Hoogmoed, 1994).

1.2 An approach for the selection of tillage practices

In this work, a soil workability based procedure is developed as a decision support tool for selecting site-specific tillage practices, considering the particular conditions of the tropics of Mexico. Prescribed tillage has been mentioned by several authors (Spoor, 1975; Hillel, 1980; Shafer et al., 1985; Tisdall, 1988; Perdok and Kouwenhoven, 1994).

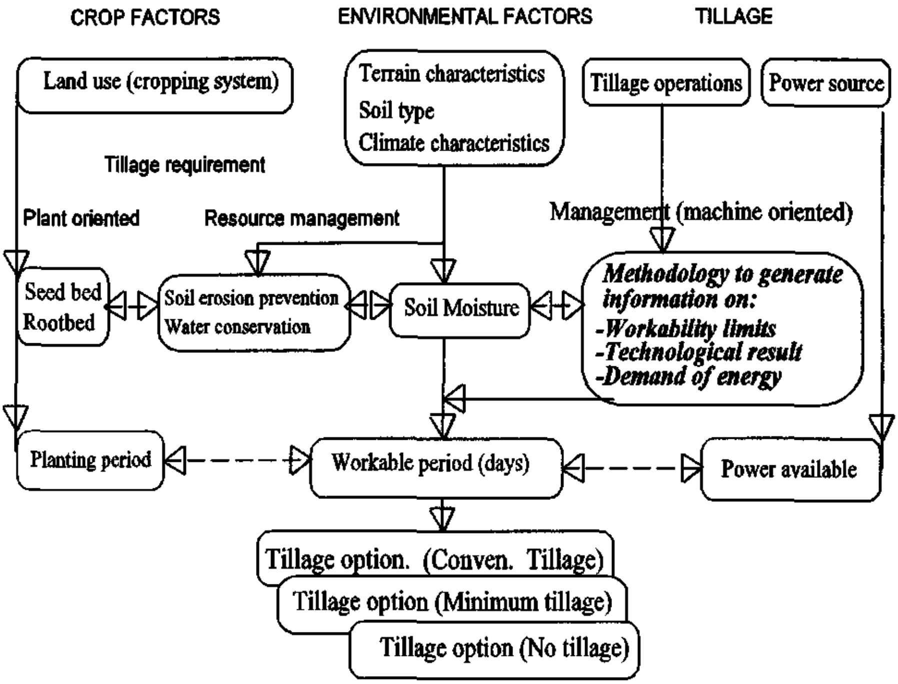


Fig 1. *Schematic representation of a workability based procedure for decision support on tillage selection and operation in the tropics of Mexico.*

Figure 1 is a schematic representation of the procedure. Local climate, soils, terrain and cropping system characteristics must determine the requirements for crop establishment, soil and water resource management and soil moisture status at time of tillage.

The tillage operations and tools must be chosen depending upon their ability to provide for the requirements within the workability limits of the soil, workable time and power available.

Quantitative information should be used when defining the requirements and describing the performance of operations. In this manner, it will be possible to judge objectively when making a decision or the best compromise.

The information obtained following this procedure should be used not only to reconsider the actual practices, but also in the land use and mechanization planning process.

1.3 Working method

The aim of the work is to generate the portion of the information needed in the knowledge base of the procedure for an objective analysis. Work has been done to develop a methodology for the generation of quantitative information and the prediction of the soil workability limits. Within this study other aspect of tillage management are involved, such as estimation of energy required.
The first version of the decision frame was developed and an expert system (a decision tree framework) was constructed for data analysis. Existing information describing local conditions is entered and treated by a systematic process, to determine the requirements to be met by the tillage operations (Fig.1.).

1.4 Hypotheses

1.4.1 General

- Failure to achieve timeliness of operations, poor results in seedbed preparation, and high costs of tillage due to the inefficient use of implements and power sources are occurring in the tropical areas of Mexico. This is because very subjective criteria are used to decide when and how to carry out tillage.
- A methodology to assist in objective selection of tillage practices in the tropics of Mexico could be constructed as follows: 1) Develop a methodology to assess and forecast the workability limits that lead to a satisfactory effect of currently used tillage practices on seedbed characteristics. This should also lead to efficient use of the available power for tillage. 2) Define quantitatively the requirements to be attained by tillage practices for crop establishment and soil water resources management. This could be done from an analysis of relevant information already available about crops, terrain, soil and climate characteristics in this region.

1.4.2 Specific

- The actual problems of poor seedbed preparation and the deficiency of timeliness in tillage practices are due to the lack of quantitative knowledge (i.e. workability criteria). There is no quantified indication in a given soil about the range of soil moisture content where an implement could create the required structure.
- Utilizing field information, it is possible to develop a method for quantifying and predicting the workability limits of a given soil.
- Field scale measurements of workability limits for specific tillage operations and soil types can be extrapolated for the prediction of optimum and

suboptimum conditions for tillage in soils with similar textural characteristics. This information forms the basis of the procedure for the recommendation of tillage practices.

- A significant reduction in the demand of energy could be achieved if tillage operations were done within established soil workability limits.
- When the energy requirement for specific tillage operations can be quantified, an adequate management of the available power (or planning of power sources) could be done in order to achieve the timeliness required for tillage operations.
- The estimation of the energy requirements for tillage operations for different regions in the tropics of Mexico could be done using a method that relates field and laboratory measurements and the available time in which operations must be conducted.

1.5 Objectives

1.5.1 General

- To develop a methodology that allows quantitative field assessment and prediction of workability limits and energy requirements for tillage operations in soils under cropping in the tropics of Mexico.
- To develop an objective-oriented procedure for decision support with respect to the selection of tillage practices in the tropics of Mexico. Emphasis is to be given here to the possibilities for the introduction and application of no-till (direct drilling) practices.

1.5.2 Specific

- To develop a method for quantitative assessment in field, of the workability limits for known tillage operations in representative soils under cropping in the tropics of Mexico.
- To link the field studies to a laboratory test for the prediction of the workability limits for different soil types in the tropical area for the recommendation of tillage practices.
- To quantify the energy requirements for selected tillage operations within workability limits, in order to establish a relationship between moisture content and energy required for a tillage operation in a given soil.
- To gain quantitative information in order to estimate the energy requirements of tillage operations for other areas of the tropics of Mexico.
- To construct an initial version of an automated procedure for the analysis of relevant data, in order to derive information to support decisions on tillage planning and management.

1.6 Synopsis

The development of the above mentioned methodology was conceived for application in the tropical area of Mexico. For this reason a description of the area under study in relation to the present agricultural production system, including tillage related problems, is presented in Chapter 2 .

To quantify the workable range of soils in the area, field studies were carried out. In Chapter 3, the methodology and results from those studies are presented and discussed, considering the technological result of the tillage operation and the input of energy at a range of soil moisture contents. The thresholds that delimit the optimum and sub-optimum results in the field shall be represented by means of laboratory tests. The methodology and results from laboratory experiments are also presented, and any links and discrepancies in representing field results are discussed. This is the main part of this research since it is the development of the methodology to characterize the workable range of soils.

Once the workable range of a soil is known, the workable period (within the cropping calendar) depends on the interactions between soil characteristics and weather. As will be discussed in Chapter 4, the data collected are used to model the soil-water balance in order to obtain the relevant information for tillage planning and operation. The possibility of deriving the hydraulic characteristics of soils from limited textural data normally available in the area under study will also be discussed as they are required by deterministic soil-water models.

The soil workability and the soil-water balance are the 'tools' to calculate the workable periods, but in this area the data available to determine both 'tools' is available at different spatial scales. The possibility of extending the methodology applied at the experimental field level to other scales will be discussed in Chapter 5.

To decide objectively which tillage practice will be chosen and when tillage should be carried out, a great deal of information has to be analysed. To take advantage of the soil workability methodology developed, it may be used within an automated procedure wherein the user needs only to supply its specific circumstances and receive as output the relevant information to utilize as support for planning decisions. In Chapter 6, an initial version of such an automated procedure is presented, and possibilities and needs for further development are mentioned.

In Chapter 7, general conclusions are stated regarding the development and use of the methodology on soil workability to support the planning and operation of tillage systems.

2 LOCATION AND DESCRIPTION OF THE STUDY AREA

2.1 Location

The area under study is located in central part of Veracruz State, on the east coast of Mexico. The latitude of the area lies around 19° North and the longitude around 96° West. Figure 2 shows a map with the location of the region where the experimental site is found, southwest of the city of Veracruz.

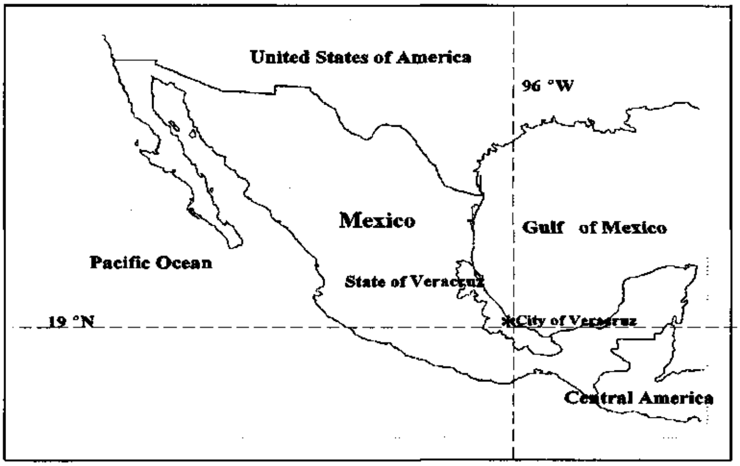


Fig. 2. *Location of the area under study in the central part of Veracruz State, Mexico.*

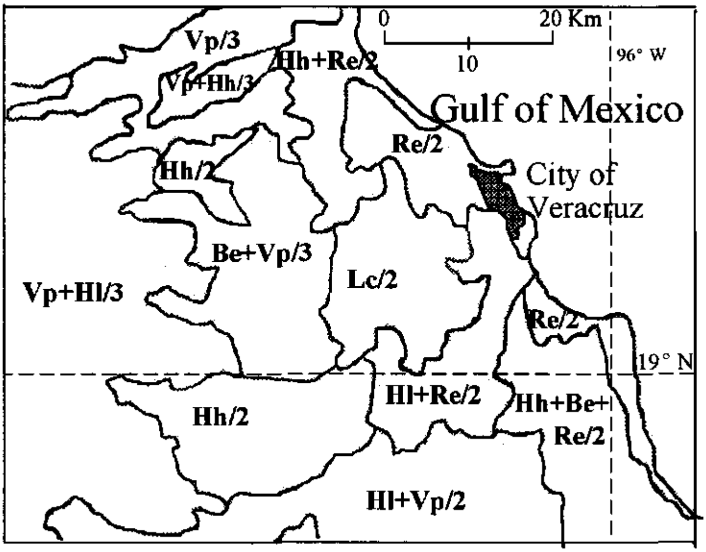
2.2 Environmental factors

2.2.1 Terrain characteristics

Agricultural activities are developed in broad terrain conditions. The region comprises a strip of coastal plain with nearly flat land (up to 5% slope). As the altitude above sea level increases from the coast to a mountain range (up to approximately 3000 m above sea level on average, 100 km away west of the coast) the terrain changes to undulating (up to around 15% slope) and hilly lands (more than 15% slope). The length of the slopes varies, according to the farm plots, from 50 m to around 200 m. As it is located in the watershed of the Gulf of Mexico, two rivers flow from the mountains across the area under study. There are several perennial and temporal streams affluent to the rivers that make up the surface drainage system of the region.

2.2.2 Soil characteristics

According to the local soils map (FAO-UNESCO classification; see Figure 3), the dominant association of soils in the area are as follows:



Key to symbols:
Re = Eutric Regosol   Hl = Luvic Phaeozem   Hh = Haplic Phaeozem   Vp = Pelic Vertisol
Be = Eutric Cambisol   Lo = Ortic Luvisol   Lc = Cromic Luvisol
1 = Coarse textural class   2 = Medium textural class   3 = Fine textural class

Fig. 3. *Main soils units in the Central part of the Veracruz State, Mexico. (Source: soil map of Veracruz State, scale 1: 1 000 000 by INEGI, 1987). Classification according to FAO/UNESCO, 1974).*

In the flat lands, soil units of Vertisols, Luvisols and Phaeozems are common. The soils under agricultural activity in this plain are medium to fine textured with a blocky structure. The *"A"* horizon is more than one metre in depth. The soils were developed from sedimentary rocks from the quaternary (INEGI, 1987, 1993).
In the undulating lands, associations of Phaeozems, Vertisols and some Cambisols are dominant. Most soils in this part of the area tend to be medium to coarse textured, with a structure in blocks. A litic phase and a stony phase are present in some of this land, and the "A" horizon is around 0.40 m in depth. The soils and conglomerates were developed from sediments from the tertiary (INEGI, 1987, 1993).
The soil associations in the area are found to offer reasonable resistance to

erosion. The erodibility index "*K*" of the USLE (Universal Soil Loss Equation) for the soils is considered medium to low, with values being approx. 0.018 to 0.020 (Uresti et al., 1993).

2.2.3 Climatic characteristics

The climate in the area of study is classified as *Aw* (Köppen system, modified by Garcia (1970)). The climate is a warm subhumid one with rainfall in summer (June to September). The average annual temperature is 26° C. In the coldest month (January) the average minimum temperature is around 20° C, in the hottest month (May) the average maximum temperature is around 30° C (Tejeda et al., 1989). The annual rainfall is around 1400 mm. Most of the rain falls between the second half of May and the first half of October. It is in this wet period that crops can grow well in the region. Soil preparation for the sowing of crops has to be done from the second half of May up to the first half of July. This is the optimum crop establishment period because if sown earlier, the crops risk heavy damage by pests when ripening takes place in wet weather. If sown later, the crop will still be in the field in November and December when strong winds cause also heavy damage.

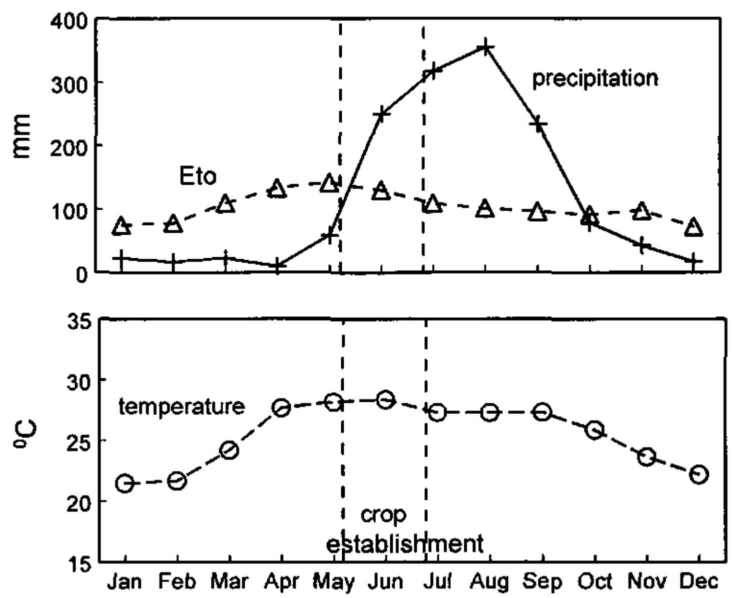


Fig. 4a. *Typical monthly precipitation, potential evapotranspiration (Eto) and average temperature for the tropical area of Mexico. (Averages for a ten year's period at the experimental site).*

Figures 4a and 4b show the monthly precipitation, potential evapotranspiration (Eto) and the temperature.
The erosivity of the rainfall, taken as the *"R"* factor of the USLE equation ranges from 8610 to 11780 MJ.mm/ha.h for the area under study (Uresti, 1992). Rainfall showing these values is considered to be potentially highly erosive.
From the second half of October to the first half of May the evapotranspiration normally exceeds the precipitation, so cropping in this season is possible only under irrigation or on water stored in the profile. Irrigation is practised in limited areas, principally for growing vegetables in the land close to the riverbanks and in the coastal plain where the watertable is from 5 to 10 m depth.

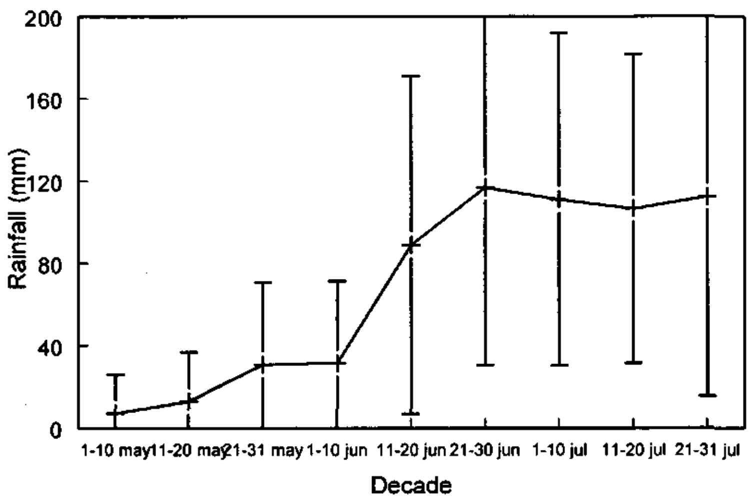


Fig. 4b. *Rainfall and variability for ten-day periods in the soil preparation period (based on rs of data).*

2.3 Cropland

2.3.1 Crops

Almost all the cropland in the area (Figure 5) is under rainfed agriculture. The cropland acounts for around 60 thousand ha, most is devoted to maize (*Zea mays*) as an annual row crop established in June-July at the beginning of the rainy season. For the season of 1997, slightly more than 41 thousand ha were established in the area with maize in rainfed conditions (INEGI, 1998). This reflects the importance of this crop as a staple food in Mexico where approximately 7.6 million ha are devoted to the growing of maize of which about 3 million are established in the tropical areas from which around 0.5 million are established in the State of Veracruz (Sierra et al., 1994). Other annual crops such as beans (*Phaseolus vulgaris*) and vegetables (under irrigation in the dry season) are grown on a smaller scale compared to maize. Mango (*Mangifera indica*) and papaya (*Carica papaya*) are important perennial and semi-perennial crops in the region.

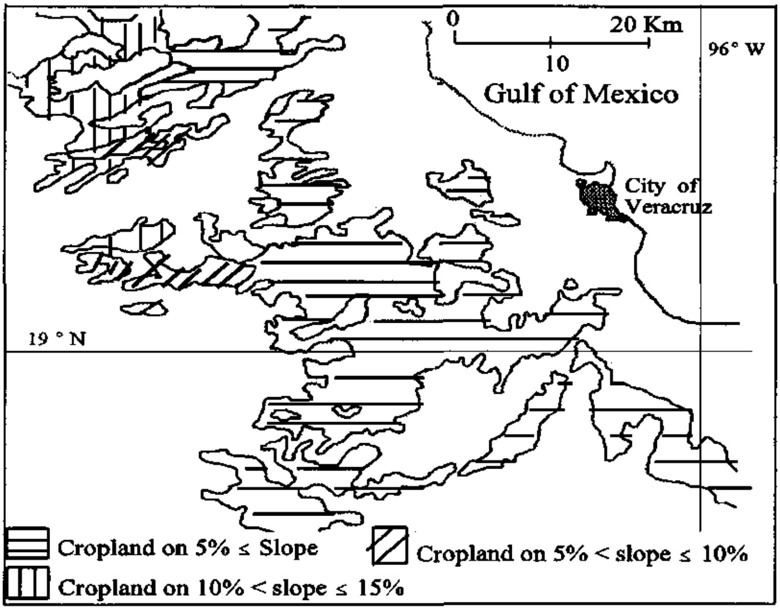


Fig. 5. *Location of rainfed cropland and their corresponding slopes in the area under study. Other area is grassland and native vegetation.*

2.3.2 Tillage practices

The production system of annual crops includes seedbed preparation for each crop cycle. Conventional local tillage system where tractors are employed involves soil loosening by ploughing with discs, then crumbling the soil to obtain finer aggregates for the seedbed through disc harrowing. When animal traction is used for tillage activities, loosening is done by a mouldboard plough. According to local reports in the area, at least 60% of the primary and secondary tillage (ploughing and harrowing) is done with tractors. In some municipalities in the region tractors are used for 90% of the primary tillage. Primary tillage (ploughing) with animal traction is performed in a range of 10 to 40% of the land. Most of the tillage operations that demand a relatively high amount of energy (ploughing and harrowing) are performed by tractors. The additional cultivation practices such as

planting and mechanical weed control are doing almost totally with animal traction and hand labour (Cadena and Peña, 1984; Sims, 1987; Uresti et al., 1993). Recently no-tillage is being introduced in the area as an alternative system for crop production.
The following problematic aspects related to tillage practices in the region have been recognized:

2.3.2.1 Soil erosion

Some farms in the area have erosion problems. According to Uresti et al. (1993), the causes are mainly related to the high erosivity of rainfall, inadequate crop management and to the traditional tillage operations (disc ploughing and disc harrowing) carried up and down slopes. Estimated soil losses in the region range from approximately 6 to 300 ton/ha.yr in different scenarios. Uresti and Cadena (1995) have evaluated the field efficiency of alternative ways ("support practices") to carry out traditional tillage operations for seedbed preparation (e.g. by controlled graded furrows, controlled graded beds). They also evaluated no-tillage as a practice for reducing soil erosion, as compared with the traditional practice of tillage operations in straight furrows for maize production under the environmental conditions of the tropical area of Veracruz. Support practices (graded furrows, and graded beds) and no-tillage resulted in soil losses of 73%, 81% and 88%, respectively, of soil losses found under the traditional practice. This reduction in soil loss was mainly due to a decrease in velocity and volume of water running off.
The same authors estimated the soil losses by applying the USLE for the plots where practices were evaluated, and the resulting reduction of soil loss rather agreed with those obtained in field, which were 76%, 86% and 78% on soil loss reduction compared with the straight furrows (running irrespective of slope). Soil losses were estimated to be 50 ton/ha.yr for the straight furrows, and 12, 7 and 11 ton/ha.yr for controlled graded furrows, controlled graded beds and no-tillage. Taking into account the soil type and depth and the relationship between erosion and productivity in Central Veracruz, Uresti et al. (1993) recommend to accept a soil loss of up to 12 ton/ha.yr as a maximum soil loss tolerance.

2.3.2.2 Soil compaction

This problem became evident in the relatively flat areas of the region under study for medium and fine textured soils, particularly after the wide introduction of tractors. Infiltration rates have decreased, leading to a rapid commencement of run off in relatively low slope values (up to 2%). On the other hand soils that were previously qualitatively judged ready to be worked soon after some rain are remaining saturated for longer periods. Figueroa (1983) states that in Mexico, the use of conventional tillage (which requires several operations, including ploughing and harrowing) increases the density and compaction of soils, thus creating a circle where more and more tillage is required. After analysing studies in several regions of Mexico, Figueroa and Flores (1992) have found that the bulk density in the arable layer has always been higher for conventional tillage compared with conservation tillage, where ploughing is not performed. Particularly in the tropical area, it has been observed in many cases that tractor operators conduct tillage when the soil profile seems to be dry enough from the surface downwards. However, the soil at the working depth for ploughing is still wet and it smears, forming a compacted layer at the working depth.

2.3.2.3 Energy, seedbed quality and operational costs

In most agricultural regions of Mexico including the tropics, tillage is performed in sub-optimum soil moisture conditions. This implies not only soil degradation, but also high expenditure of energy and low efficiency of the tractor-implement system (Pineda et al., 1996). This is a particular occurrence in the area under study as shown in Figure 4 as the transition from dry conditions to wet conditions will be a rather short period, the optimum (workable) time must be carefully determined in order to plan and operate tillage systems as efficiently as possible. However as elsewhere in the country, this soil workability information is not available.

After conducting an analysis of crop establishment in the rainfed areas of the tropics of Mexico, Campos (1993) concluded that there is an intensive use of hand labour for sowing and planting operations. Mechanical planters have not been commonly used because of their poor performance under local conditions of soil preparation, resulting many times in poor stands and consequently low yields. The intensive use of hand labour for planting and fertilizer application results in a higher cost of crop production, timeliness penalties due to later crop establishment, and leads to suboptimum land use.

3 SOIL WORKABILITY

3.1 Basic aspects of workability: a literature review

3.1.1 Soil aspects

3.1.1.1 Defining soil workability

The workability of soil indicates the condition when tillage operations can be performed for making the desired structure and shape of its surface (Goense, 1987). If seedbed preparation is the required operation, the soil is considered workable when conditions are suitable for the production of a friable tilth without smearing or compaction (Rounsevell and Jones, 1993). In land evaluation (FAO, 1983) workability is a land quality that describes how easily the soil can be cultivated or tilled. It is assessed according to the texture/ structure/ consistency relationships of the topsoil. Workability varies from soil to soil, machine to machine, and from one farm operation to another (Simalenga and Have,1992). This variation is influenced by the transient moisture content as much as intrinsic soil properties such as clay or organic matter (Thomasson, 1982). When assessing workability it must include a time element involving the duration of good conditions during the cropping calendar for soil-engaging operations (Spoor, 1979).

In practice the condition of soil for carrying out the tillage operations is judged by the farmer rather subjectively: this being particularly true in the tropics of Mexico. As a result, problems caused by tillage under poor conditions, such as poor seedbed preparation, compaction, and very high expenditure of energy may arise, and other tillage operations may be required to correct the condition left by a previous one. Campos (1993) describes the problems related to poor soil preparation in the tropics of Mexico. One major problem is the poor emergence of maize and beans under mechanized planting, because very often an adequate soil structure is not achieved due to the subjective evaluation of soil condition for seedbed preparation.

Workability not only depends on the results of tillage operations, but also on the energy required, so an optimum ratio of tillage results to energy consumption is pursued (Tijink, 1988). Currently, the cost of tillage accounts for about 40% of the total production cost of the main crops in the tropical area of Mexico, and since this is a main constraint for crop production, attention must be paid to the energy aspects (Cadena et al., 1993). If tillage is done in a defined initial soil condition there would be a better chance of having the required results from one operation. This should contribute to efficient energy consumption by tillage, thus avoiding

extra costs. So it is necessary to have quantitative information about the workability limits in the field.
However, before an optimum cultivation treatment can be decided upon, the soil's required physical environment must be clearly defined. This environment may have to satisfy the needs of the plant, mechanization and/or soil and water conservation (Spoor 1975).

3.1.1.2 Tilth to be attained

(a) <u>Soil condition required for seedbed</u>
The required soil tilth can be defined in terms of range of aggregate size distribution in the seedbed layer or planting row, surface micro relief or bulk density. These values are related to the requirements for crop establishment and emergence or/and soil and water conservation. The quantities can be defined according to those reported in the literature as results of previous work, or by translating the qualitative description of required seedbed condition into quantities that represent the tilth. To give an example, the aggregate size in the seedbed is considered as follows. For the good germination and emergence of maize, the aggregates in the seedbed should be in an optimum size range of 1 to 8 mm, according to the review of Braunack and Dexter (1989). This apparently wide range is due to the relatively large size of maize seeds. Braunack and Mc Phee (1991) define a suitable seedbed as one containing approximately 66% of aggregates between 1 and 15 mm. It is clear that most seeds need small aggregates in the vicinity for an adequate transfer of moisture for germination. This is especially true for mechanized planting, where the press wheel should cause a localized increase of soil density around the seed and relatively small aggregates are needed to achieve this.
In the tropical area of Mexico, one of the main limitations of the use of mechanized planting is the poor soil preparation mentioned earlier. Consequently even if the farmers use tractors for primary operations they prefer to plant using manual labour. When planting by hand, the final quality of the tillage does not matter very much if after depositing the seed the clods can be pressed by foot achieving generally a good soil-seed contact. However, planting and fertilizing with manual labour is limiting in terms of timely operations, so the areas to plant are reduced due to labour availability. Financial studies in the region have shown the advantages and the increased economic benefit that mechanized planting has over the manual system (Jacome Maldonado, 1989).
Crops demand a good structure that can provide appropriate levels of temperature, air, water and nutrients. Land is tilled in order to create an environment which promotes germination, emergence and growth of seedlings. The availability of

water and nutrients to roots depends upon the roots being able to move freely into the soil and exploit the reserves stored there. Different crops demand specific seedbed conditions, and the tillage management system should be aimed at achieving those conditions. However, in many places tillage practices are still rather standard for one crop in different environments, and even for different crops. Hillel (1980) suggests an approach to soil structure management for row crops. A planting zone where conditions are to be optimal for sowing and conducive to rapid and complete germination and seedling establishment, an other being the management zone in the interrow areas where soil structure is to be coarse and open, allowing maximal intake of water and air, and minimal erosion and weed infestation.

Ideally, the requirements should be formulated from the results of quantitative controlled experiments (Tisdall and Adem, 1988; Spoor, 1975). In fact, if the information is available the desired physical condition should be described quantitatively. Several authors have studied the requirements of crops regarding the most suitable aggregate size distribution in the seedbed for a good germination. Braunack and Dexter (1989) have done an extensive literature review about the effect of aggregate sizes on plant growth, which provides an insight into the consequences of using different soil structures on crop establishment. Tillage is used to control the distribution of aggregates in the profile, and a resultant aggregate size distribution depends heavily on the moisture content at the time of tillage and the type of tillage implement used (Larney and Bullock, 1993). Though recommendations would only be applicable under specific conditions of soil type, soil moisture, and crop species being grown, it is very important to know the particular range of moisture content and the appropriate tool for making such a convenient seedbed. Aggregate size requirements vary according to the size of the seed, and should lead to maximize seed-soil contact for germination. Hadas and Russo (1974) suggest that aggregates should be one fifth to one tenth the size of the seed. In relation to specific aggregate size requirements for maize, Tisdall and Adem (1988) set specifications based on the literature, for the physical soil properties of a seedbed that do not limit water movement, germination of maize seeds, root growth and earthworm activity. To meet the physical properties in terms of aggregates, a size range of 0.5 to 2 mm was specified in the seeding zone, this size was about 20% of the diameter of the maize seeds used. In the root zone, the size of aggregates was from 1 to 10 mm. The tillage management used (prescribed) was aimed to get this condition.

Table 1 shows optimum size ranges for various crops, compiled by Braunack and Dexter (1989). Table 2 shows their description of the seedbeds which provide optimum physical properties. It seems that most seeds need small aggregates in the vicinity for an adequate transfer of moisture and nutrients for germination.

Schneider and Gupta (1985) found in a growth chamber experiment that maize emergence was most rapid when aggregate size distribution corresponded to a geometric mean diameter (Mean Weight Diameter) between 1.0 and 6.8 mm, when the soil moisture was above field capacity and when soil temperature was between 20° and 30°C.

Table 1. *References which quote given aggregate size ranges as being optimum for various crops (after Braunack and Dexter, 1989).*

Aggregate size range (mm)	Cereals	Maize and Sorghum	Soya Bean	Sunflower	Tomatoes
< 1	Edwards (1957) Thow (1963)			Miller and Mazurak (1958)	
1 - 2	Dojarenko (1924) Nijhawan and Dhingra (1947) Jaggi et al (1972) Njos (1979) Hakansson and von Polgar (1984) Braunack and Dexter (1988) Russel (1973)	Baligar and Nash (1978) Tisdall and Adem (1986) Russel (1973)	Nash and Baligar (1974) Russell (1973)	Russell (1973)	Lemon and Erickson (1952) Russell (1973)
2 - 4	Kvasnikov (1928) Nijhawan and Dhingra (1947) Hagin (1952) Braunack and Dexter (1988) Njos (1979)	Johnson and Taylor (1960) Taylor (1974) Baligar and Nash (1978) Russel (1973) Tisdall and Adem (1986)	Nash and Baligar (1974) Russell (1973)	Russell (1973)	Lemon and Erickson (1952) Doyle and Mac Lean (1958) Russell (1973)
4 - 8		Larson (1964) Baligar and Nash (1978) Tisdall and Adem (1986)			

Bernsten (1982) suggests that the quality of soil preparation may be evaluated principally through the seedbed aggregate size distribution, the depth of seedbed and the evenness of the bottom and the surface.

The same author mentions that the best emerging conditions for cereals occur when a high proportion of the aggregates in the seedbed is in the fraction of 0.5-6.0 mm, and when the fraction of aggregates larger than 20 mm is small. Adem et al. (1984) state that authors disagree as to which range of aggregate size provides the ideal seedbed, but most suggest low amounts of dust (< 0.5 mm diameter) and clods (> 20 mm diameter). In the tropical area of Mexico, cloddy seedbeds, quantitatively found to have a mean weight diameter of more than 20 mm (Cadena et al., 1996), lead to poor stands when planting by machine

(Campos, 1993). In Mexico, there is a need to define initial soil moisture conditions to get an adequate seedbed after tillage (Pineda et al., 1996), because while working in to dry or wet conditions, several passes of implements are currently needed to reduce the size of aggregates.

Table 2. *Desirability scores for different aggregate size ranges for some principal physical properties of seedbeds (after Braunack and Dexter, 1989).*

Aggregate size range (mm)	*Lowest evaporation*	*Greatest intra-aggregate aeration*	*Greatest inter-aggregate aeration*	*Least wind and water erosion*	*Lowest compactability*	*Sum of properties*
0.1 - 0.2	*1*	*3*	*1*	*1*	*1*	*7*
0.2 - 0.5	*2*	*3*	*1*	*1*	*1*	*8*
0.5 - 1.0	*3*	*3*	*2*	*2*	*2*	*12*
1.0 - 2.0	*3*	*3*	*3*	*2*	*2*	*13*
2.0 - 4.0	*2*	*2*	*3*	*3*	*2*	*12*
4.0 - 8.0	*2*	*2*	*3*	*3*	*2*	*12*
8.0 - 16.0	*1*	*1*	*3*	*3*	*2*	*10*

(b) Soil condition for root development

In the rootbed, the structural features of the soil influence growth after emergence. The condition of the seedbed is important only on the first days (Wilkinson and Braunbeck, 1977; Braunack and Dexter, 1989) whereas the rootbed is the structure that influences the development of the plant for the rest of its life cycle. Because of this, care must be taken so that the finishing of a seedbed is not detrimental to the soil layers below where the majority of roots will develop.

The soil condition needed is one comprising a network of continuous drainable pores, so the soil should be not too compact (Spoor and Godwin, 1990). A well-structured rootbed allows the extension of roots through the pore space between the soil granules, the movement of air and water, and the maintenance of a good soil-root contact for water-nutrient uptake. Bulk density and penetrometer pressure (penetration resistance, cone index and strength) are the parameters related to mechanical impedance for root growth (Glinski and Lipiec, 1990). The compactness of a soil greatly influences root and plant development; a condition which is too loose is as detrimental as one that is too dense (Spoor and Godwin, 1990). This is shown in Figure 6, which shows ranges of porosity and moisture suction delimiting optimal root growth conditions, bordered by threshold levels of mechanical resistance and aeration, a concept of critical soil density/porosity as proposed by Boone (1988).

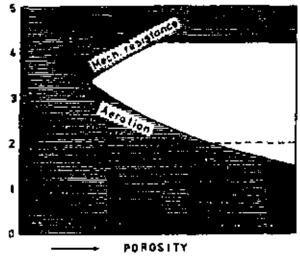


Fig. 6. *Optimal root growth conditions (non-shaded area) as a function of porosity and moisture suction (after Boone, 1988).*

Singh et al. (1992), when characterizing a soil tilth index, proposed that any soil with a bulk density less than or equal to 1.3 g cm^{-3} can be considered non-limiting for root growth, but from this point limitations start to build up and a bulk density of 2.1 g cm^{-3} be considered unusable by the plant. This latter value is only theoretically high as bulk densities of 1.5 g cm^{-3} may already hamper root penetration (Lal, 1995). Maize root length sharply decreased with increasing bulk density of a loamy sand from 1.2 to 1.7 g cm^{-3}, as found by Shierlaw and Alston (1984).

The studies of Gerard et al. (1982) show that in two soils (sandy loam and clay loam) the root growth of cotton seedlings at different depths was significantly influenced by soil strength, volumetric water content, voids and clay content. The critical strength, defined as the probe pressure (in bar; penetrometer cone) at which root elongation stopped, was a function of the clay content. The critical strength ranged from 60 to 70 bar in coarse textured soils to 25 bar in clay soils. Ehlers (1982) found that in an untilled loess soil, root growth stopped at a probe pressure of 46 to 51 bar in the Ap horizon (0-25 cm) whereas in a tilled treatment of the same soil and horizon, root growth stopped at a probe pressure of 36 bars. Within the top 20 cm layer of the Ap horizon bulk density was higher on untilled soil (1.4-1.5 g cm^{-3}) as compared to tilled soil (1.3-1.4 g cm^{-3}). In tilled soil, however, bulk density increased at about 25 cm depth to 1.55 g cm^{-3}, indicating the presence of a traffic pan. The explanation for root growth at higher probe pressures in untilled soil was that the roots of a following crop can re-enter biopores created by earthworms and by roots of preceding crops.

In tropical areas, soil compaction is a major constraint to continuous cultivation and high yields, especially when intensively used. Luvisols are easily compacted and attain critical levels of soil bulk density within 2 to 3 years after bringing land under cultivation (Lal, 1995). Critical soil density values for root penetration and crop growth are not known for some of the major soils of the tropics, but bulk densities of 1.43 g cm^{-3} and 1.50 g cm^{-3} are reported as upper values for optimal yield of maize and sorghum in tropical countries (Couper et al., 1981; Willcocks, 1981).

(c) Soil condition for the prevention of erosion by water

According to Lal (1995), in the tropics, the effects of tillage on soil properties and on the erosion risk are hard to generalize. These effects vary greatly. For example where the soil has a favourable structure, with a high proportion of water-stable aggregates, and is permeable, mechanical soil disturbance for crop establishment is likely to increase the risks of soil erosion. On the other hand, where the soil has a smooth crusted surface and compacted subsoil horizons, massive non porous unstable structure, carefully-judged, timely mechanical tillage is likely to decrease the risk of soil erosion (Hoogmoed, 1999).

Cultivation based on ploughing and harrowing provides a weed-free seedbed with smooth soil conditions for crop establishment. However, this is in conflict with the requirements to prevent soil erosion (soil protective cover and/or rough surface). In the particular situation of the tropical area of Veracruz, Mexico, soil losses were decreased (after carrying out the cultivation practices, ploughing and harrowing) by planting the crop in controlled graded furrows; in this case by reducing the velocity (allowing more time for infiltration) and thus reducing the volume of runoff, soil losses were diminished similarly as when using a no tillage system (Uresti and Cadena, 1995).

3.1.1.3 The role of soil consistency

Some authors (Spoor 1975; Krause et al., 1984; Ashburner and Sims, 1984) have described the effect of moisture content on the consistency and workability of the soil. The soil fails mainly in shear. Figure 7 shows how the soil shear strength varies within the different consistency states. According to Spoor (1975) and Krause et al. (1984), two types of shear strengths can be distinguished in a structured or cloddy soil: one is clod shear strength, which is due mainly to molecular cohesion and organic bonds. The other is the bulk shear strength, due mainly to friction and film cohesion. The higher the shear strength, the greater the chance that the soil can withstand externally applied loads with little compaction. Soil material is not tillable when wet and unstable, because the fragile soil matrix is easily destroyed (Perdok and Kouwenhoven, 1994). But in dry soil, the higher the shear strength, the greater the effort (energy) required to rearrange the soil material. Therefore in between dry and wet, there is an optimal moisture range for working the soil.

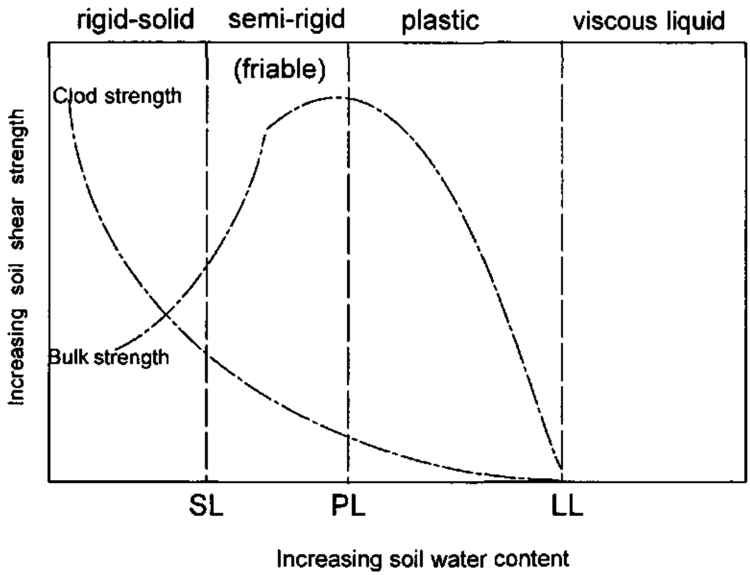


Fig. 7. *Soil consistency and Atterberg limits. The friable condition is theoretically the best workable. SL: shrinkage limit, PL: plastic limit, LL: liquid limit.*

The soil consistency refers to the characteristic of a soil that causes it to remain "consistent" under stress or maintain its shape when subjected to deformative forces (Hillel, 1980). The empirical criteria aimed at making some measure of consistency are known as the Atterberg limits (Chancellor, 1994). These limits are described as follows: a) the liquid limit (LL) or upper plastic limit is the soil moisture content at which the soil-water system changes from a viscous liquid to a plastic body; b) the plastic limit (PL) or lower plastic limit is the moisture content at which the soil changes from a plastic condition to a semi-rigid friable state as moisture decreases, and c) the shrinkage limit (SL) is the moisture content at which the soil changes from a semi-rigid to a rigid-solid with no additional change in specific volume as soil is drying out. Atterberg limits are shown in Figure 7.

3.1.1.4 The soil failure process

Following the definition of the optimum (ideal) soil condition required for crop establishment and soil and water conservation, it is necessary to determine the optimum way of transforming the soil from its present state into that required. The existing soil condition before tillage will dictate the nature of the transformation, i.e., to form or destroy soil aggregates, alter the clod size distribution, rearrange the soil particles and aggregates by either loosening, compacting, puddling, inverting, mixing, smearing or transform the soil surface by either smoothing, moving or forming (Spoor, 1975).

The performance of a tillage tool is defined as the production of a change in soil conditions by mechanical manipulation. Tool shape, direction and speed of movement and the initial soil condition entirely determine the resultant soil condition and the magnitude of the forces required to move the tool (Gill and Vanden Berg, 1967). In terms of suitability of soil conditions performance must be evaluated by comparing the final soil conditions that are produced with those that are desired. Performance, in terms of forces must be evaluated by comparing forces required for manipulation with available or acceptable forces.

Hillel (1980), points out that when it is possible to define the application of forces to the soil and the soil reactions to variously applied forces, it is possible to predict the final soil condition and to what extent it will approximate a desired state, after given the initial soil condition and the characteristics and mode of operation of a given tool.

According to Spoor (1975), whenever a force is applied to soil by implements or tractors, some deformation must occur to enable a resisting shear force to develop which is equal and opposite to the applied force. The amount of deformation resulting from a given applied force depends upon the soil type and its condition.

The failure of a soil by an implement can be classified into two types: brittle failure and flow or compressive failure (Stafford, 1982). These two types of soil deformation may be related to the requirements of certain cultivation operations, i.e., when the soil mass must be fissured and loosened,or when reducing the clod size for seedbed preparation by cracking and fissuring, the soil deformation can be likened to brittle failure (Spoor and Godwin, 1979). In cultivation practice, brittle failure is desirable, and flow or compressive failure is undesirable (Stafford, 1982). However, very often in tillage operations when carrying out an intended process, another "accidental" one could occur i.e., in seedbed preparation the major intended process is "crumbling" (brittle failure) and this process is accompanied by the accidental process of "compaction" (Tijink, 1988). The failure of the soil is influenced by the interaction of a number of soil-implement factors; soil moisture content and density, implement speed, depth and geometry (Stafford, 1981).

A relationship should be established between the initial conditions of soil and the effect of the implement, in order to establish when the aim of tillage can be achieved. Workability has also to do with the deformation characteristics of a soil as it is subjected to a system of stresses (Stafford, 1982). The principal factors that influence the magnitude of main stresses in the field are the magnitude of the shearing resistance deforming the soil (affected by soil density and moisture content), the direction of loading and the strain imposed by the implement, as affected by the implement geometry (Spoor and Godwin 1978, Stafford 1981, Perdok and Kouwenhoven 1994).

3.1.1.5 Assessing workability limits

(a) <u>Evaluating a wet workability limit</u>

If the initial soil conditions such as moisture content and density are known and the aim of tillage is to loosen a precompacted soil, it could be said that the loosening process (brittle failure) is occurring if the soil density is decreased and the larger structural units are broken down into smaller units. Thus there is a general decrease in soil density and it is assumed that the physical soil conditions specified as requirements are being attained (i.e. desired aggregate size range) with the tillage operation. If the effect of the tillage is a general increase of soil density, small structural units coalesce into larger units (Stafford 1982), which in turn will result in a large decrease in the size of pores (Slowinska-Jurkiewicz, 1994). This change will lead to a drastic drop of air permeability due to the large pores disappearing first (Perdok and Hendrikse, 1982); then there is a compressive flow failure occurring and the process has changed to compaction. This situation is more likely to occur at high moisture contents, and the upper limit of workability is found below this moisture value.

(b) <u>Evaluating a dry workability limit</u>

At low soil moisture contents it is assumed that only loosening processes (brittle failure) will take place, but as the soil dries out, it will attain a condition at which the clod and aggregate strength is very high, and any work done on the soil simply rearranges the clods without breaking them (Spoor, 1975). Tillage of massive, dry soil produces hard and coarse clods, and requires more energy compared with tilling a soil within an optimal moisture range (Perdok and Kouwenhoven, 1994). In such condition the resultant aggregate size distribution is closer to the specified requirement. Gill and Mc Creery (1960) developed a method to logically relate clod size to soil forces on the basis of energy. By repeated droppings, different amounts of energy could be used to shatter the clods and an energy-clod size relation could be obtained for a given soil condition. They suggest that the energy-clod size relation can be used as a basis for determining the amount of effective work done to a particular soil by a tillage tool. Hadas and Wolf (1984), using a drop-shatter method, found a good relationship between energy applied and reduction of aggregate diameter in air dry clods. It is important to take into account that if too much work is done to the soil (high input of energy) to reduce the size of aggregates, the net effect after the tillage operation is a higher risk for an increase in soil density under rainfall and traffic because of the loss of porosity. Such effects can occur in high speed soil cutting and shattering operations using rotary cultivators (Stafford 1982).

3.1.2 Energy aspects

Tillage operations are highly energy-consuming. The amount of work involved in repeatedly loosening, pulverizing, inverting, and then recompacting the topsoil is considerable (Hillel, 1980). Primary tillage largely dictates the power requirements on an arable farm. The weight of the tractor and implement and the process chosen for cultivating the soil will determine not only the traction available but also the draught required for a given soil type and condition (Witney and Eradat Oskoui, 1982). Energy and time spent by people, animals, and/or power units together with associated tools, implements and machinery, dictate the cost price levels of soil tillage (Perdok and Kouwenhoven, 1994). Draught requirements of tillage tools and implements are therefore an important consideration in selecting tillage systems (Summers et al., 1986).
The most important factors affecting the draught required by a tillage operation are soil type and condition, type of implement, depth of tillage, and working speed.
The power is a function of the draught and the speed of work, but the efficiency of the power source used will depend on the condition of the top soil. The traction condition is important, as the power needed for a given operation will increase due to wheel slip and rolling resistance losses (Perdok and Van de Werken, 1983).

3.1.2.1 Soil type and moisture content

Certainly, more power is required to operate the same implement in clay and other heavy soils than in sand or loam at comparable densities and moisture contents (Buckingham, 1976). According to the study of Perdok and Van de Werken (1983), the tractor power required by a mouldboard plough working on different soils under good traction conditions could vary from 20 kW per metre of working width on sand, to almost 90 kW per metre on heavy clay. The draught resistance may show considerable variation due to differences in soil moisture condition in the field (Canarache, 1987).
The most appropriate assessment of the effect of soil moisture for use in cultivation is through its soil consistency (shown in Figure 7). If the soil is dry, the shear strength of the aggregates is very high, so a high draught is required to

break the soil. As moisture content increases, the strength of soil aggregates decreases. The soil is most workable and could be manipulated with relatively little effort in a friable consistency, with a minimal risk of structural damage, this is because the bulk strength exceeds the clod strength, allowing the clods to be broken naturally along their weakest planes. As the moisture content further increases, the soil reaches a plastic consistency. In this state the clod strength is very low compared with the bulk strength, so aggregates can be readily broken and the risk of puddling, smearing and structural deterioration increases. Also, the sliding resistance between soil and implement increases to a maximum at the sticky point (Spoor 1975; Krause et al., 1984). The range of each state of consistency varies according to the soil texture, which is the main intrinsic soil property affecting its workability. Canarache (1993) describes a model (based on field and laboratory measurements) which estimates the variation of the soil specific resistance to ploughing as affected by clay content, bulk density and moisture content. From the application of this model, it was found that the minimum resistance to ploughing of heavy, clayey soils could be more than three and a half times greater than that of light, sandy soils, and it was almost three times greater in severely compacted soils than in very loose ones. As for the effect of soil moisture content, the increase in resistance to ploughing from optimum to extremely dry or extremely wet soils varied from less than 5% in sandy soils, to more than 20% in clayey ones. The range of specific resistance to ploughing in such conditions was from approximately 10 kgf dm^{-2} (10 kPa) to more than 100 kgf dm^{-2} (100 kPa).

3.1.2.2 Depth of tillage

The consumption of energy increases steeply as the depth of tillage increases. The cost of deep ploughing (to a depth of 45-50 cm) is roughly double the cost of moderately deep ploughing (to about 35 cm), quadruple the cost of normal ploughing (to about 25 cm deep) and tenfold greater than the cost of shallow ploughing (approximately 15 cm deep). The cost refers not only to the increase of draught, resulting in a higher fuel consumption, but also to the extra costs due to the need for heavier equipment and more powerful tractors, and the increased wear and tear of equipment. Buckingham (1976) points out that it is usually best to plough as shallowly as possible in order to save time and fuel due to a lower draught, provided the desired objectives of covering trash, aerating the soil and providing suitable seedbed and rootbed are met. The "ecoplough" system (Perdok and Kouwenhoven, 1998), a recent development in the Netherlands, is an example of such an approach.
According to the review of Bashford et al. (1991), much of the literature supports

a simple linear function, relating implement draught and implement depth. The draught increases approximately linearly with the depth increase, up to a value of depth where the width of the cut of the plough becomes restrictive (Hoogmoed 1994). Iqbal et al. (1994) also found a linear relationship between the draught required and the depth of operation for the cultivator, chisel plough and subsoiler, but a curvilinear relationship for disc plough and disc harrow.

3.1.2.3 Type of implement

The shape or geometry of a tool has an influence on the required draught, and it is related to the intensity of cutting or soil manipulation. Since a mouldboard plough has a more intensive soil manipulation than the chisel plough, the draught will be higher, and will also increase more quickly for heavier soils (Hoogmoed, 1994). PTO driven implements apply higher cutting and stirring intensities than the drawn implements, so the demand of tractor energy would be higher as well. In drawn implements, the rake angle also has an influence on the draught, as can be seen from the studies of Stafford (1981) concerning the performance of rigid tines, where the draught force for a tine with a rake angle of 45° was about half of that required for a tine with 90° at the same soil, moisture, speed and depth of work.

3.1.2.4 Working speed

According to Buckingham (1976), draught of most equipment increases much more than proportional with speed. Excessive speed may increase fuel consumption, wear, damage, downtime, and time spent in unplugging equipment. Singh et al. (1979), found (contrary to Buckingham) a less-than-linear increase in specific draught with an increase in speed. For a disc plough working in a clay soil with a moisture content of 27.8%, the specific draught increased from 150 kPa at a speed of 0.2 m s^{-1} to 200 kPa at a speed of 1.2 m s^{-1}. Summers et al. (1986), working with different implements and soils in Oklahoma, USA, found that the increase in draught is linear with the increase of speed for chisel plough, disc and sweep ploughing.

The peripheral speed of pto-powered tools (i.e. rotary tiller) exceeds the forward speed of drawn implements (Perdok and Van de Werken, 1983). This results in a very high consumption of specific energy to the soil which could be several times greater than that required by drawn implements (Buckingham, 1976). In cohesive soils with poor workability, pto-powered implements perform better than drawn implements because of their ability to manipulate soil in a desired manner by control of both forward and rotational speed.

3.2 Developing workability criteria to support decisions on tillage

As mentioned in Chapter 1.5, a quantitative assessment and prediction of the workable status of soil is necessary when this information is to be incorporated in a procedure for planning and operation of tillage systems. In the following chapters, field work is presented and analysed in relation to a methodology for quantifying the workable status of the soil.

For the development of the methodology to establish the workability criteria, it is necessary to look at the workable range in the field for a soil type (i.e Loam soil) and try to represent this range by some laboratory tests. Then, once the method is developed, the workable range of similar soils can be determined for other places by applying the tests.

3.2.1 Field experiments on soil aspects

3.2.1.1 Materials and methods

The field work was performed in the period 1996 to 1998 at the farm of Cotaxtla Research Station and in its surroundings. The station is part of the National Institute for Agricultural, Forestry and Livestock Research (INIFAP) in Mexico (for location see chapter 2). The experiments were located in three soils representing the broad textural classes of soils (fine, medium and coarse) of soils at the central part of Veracruz State, in the tropical area of Mexico. Conventional tillage (disc ploughing and disc harrowing) is normally carried out for primary tillage and seedbed preparation. No-tillage is starting to be used as alternative for crop establishment. The power sources used in the region for tillage are tractors and animal traction.

a) <u>Materials</u>

Soils

Table 3 shows the mechanical composition and organic matter content of the soils under study. Table 4 shows the moisture retention characteristics including the relevant range for this study (pF 2.0 to pF 3.9). Detailed experiments were carried out in two soils: Cecot-1 which is a medium textured soil and from here on it will be named LOAM, and Cecot-2 which is a fine textured soil and from here on will be named CLAY. Both are located in the research station. Some measurements were taken in soil Bautista (coarse textured soil) in a nearby farmer's field. From here on, because of its high sand content, this soil will be named SAND.

In order to establish "benchmark" moisture contents to be used in the field work, the Atterberg limits were taken as a reference. It was assumed that from the shrinkage limit that may occur above or below the permanent wilting point (PWP) (Archer, 1975), up to the lower plastic limit that may occur at 95% of field capacity (FC) the soil could be worked "easily" (Simalenga and Have, 1992). Thus tillage operations could be carried out at values of soil moisture content inside and outside of the theoretical friable range, assuming that the technological effect of a given operation at the moisture content inside the limits to be established will be the same.

Table 3. *Mineral composition and organic matter of the soils under study.*

Soil	depth (cm)	% Clay	% Silt	% Sand	% OM	Texture
Cecot-1	0-15	26.3	38.3	35.3	2.3	loam
(LOAM)	15-30	30.3	42.3	27.3	1.3	clay loam
Cecot-2	0-15	50.3	31.0	18.6	3.9	clay
(CLAY)	15-30	57.9	22.7	19.3	1.7	clay
Bautista	0-15	13.8	39.0	47.2	2.0	loamy sand
(SAND)	15-30	22.8	37.0	40.2	1.4	loamy sand

Table 4. *Particle density and pF determinations of the soils under study.*

Soil	Cecot-1 (LOAM)	Cecot-2 (CLAY)	Bautista (SAND)
Particle density (g/cm^3)	2.6	2.5	2.6
Moisture content (% w/w) at pF values			
pF 1.0	29.6	34.9	29.8
pF 1.5	27.5	32.2	27.9
pF 2.0	25.4	29.5	25.3
pF 2.3	23.8	28.3	22.5
pF 2.7	22.4	26.8	20.5
pF 3.0	22.0	26.9	20.4
pF 3.4	19.8	24.8	17.1
pF 3.9	16.3	22.3	12.9
pF 6.0	4.5	7.0	3.5

Power sources and implements

Mechanical traction (tractor) and animal traction (oxen) were used to perform tillage operations. Details are given in Annex 1.

Instrumentation

Instruments for measuring surface relief, penetration resistance, and mean weight diameter of aggregates and for collecting samples for moisture content and bulk density determinations are described in the section on data collection.

b) Methods

Field layout with mechanical traction

For the medium textured LOAM soil the field work was carried out at six moisture levels: three inside the theoretical friable (workable) state, two dry, i.e. below the shrinkage limit (SL) and one wet, i.e. above the plastic limit (PL). Conventional tillage with a disc plough and no-tillage (direct drilling) were carried out in this soil. Experimental plots (5 m x 50 m) were replicated four times for each moisture level. For the statistical analysis of the data, a split plot experiment with the tillage systems (conventional tillage and no tillage) as main plots and the six moisture content values as the splits was considered. Because the number of experimental plots (6 X 4) to be sampled (making as well replications of data collection inside the plot), the work in this soil was carried out during the dry season to avoid interference by the rain in the control of moisture.

Each experimental plot was moistened by surface irrigation until a saturated profile in the 0-30 cm depth was reached. As the units were drying out, the moisture content was monitored at intervals of 5 cm. The final moisture level was an average of the profile mentioned. Each block of four replications represented one moisture level. The tillage operations were performed one after another so the technological effect could be related to the same soil moisture content.

For the CLAY soil the work was carried out at four levels of moisture content: one located just at the SL, two inside the theoretical friable range and one wet condition, above the PL. Conventional tillage was carried out in this soil. Taking into account the homogeneity of the soil and the replications of data collection to be made inside each experimental plot, it was decided to carry out just one replication at each moisture level for this soil.

On the SAND soil, work was performed at only three moisture levels. Because the soil has a low clay percentage with hardly any workability problems, it was decided that the results would be observed just when the soil was dry, moist and wet. SL and PL were very difficult to establish for this soil. Conventional tillage was carried out in this soil. For the same reasons stated above, only one replication (experimental plot) was made for each moisture level for this soil.

Field layout with animal traction

For the animal traction, experiments were performed only on the LOAM and CLAY soils. Experimental plots were 5 m x 20 m. Tillage was carried out by ploughing with a mouldboard plough at three moisture levels. It was decided that results would be observed at those soil moisture conditions where the trainer of the animals would judge qualitatively that these were the driest and wettest conditions for working at each soil. Also a third point in between these extremes was observed.

Data collection for each experimental plot

Before running each experiment, initial conditions were determined:

- Description of previous management. This was information about the crop established, and tillage practices carried out in previous years.
- Soil moisture content was measured with depth. Sampling was done at intervals of 5 cm downwards up to 25 cm depth using a gouge auger. Then the gravimetric water content was determined, and the value of each interval was from five replications.
- Penetration resistance. Cone index was measured using a cone penetrometer. The characteristics of the probe are: cone top angle 30° and cone base area 71 mm^2. Measurements were taken from 0 to 25 cm depth at intervals of 5 cm. The measurement of each interval was replicated ten times.
- Soil density. Core samples were taken, avoiding too dry conditions to minimize the risk of disturbance. A pre-sampler and core auger were used to take the samples every 5 cm from top to 25 cm depth. Six replications were made for each interval.
- Surface relief . Using a reliefmeter, the heights of 400 points (in rows of 20 points, one point every 10 cm) at each experimental unit were measured, following the procedure described by Kuipers (1957). The apparatus was leveled, having two reference points (wooden pegs) outside the plot.

After the tillage operation the data collection was made as follows:

- Surface relief. Having the wooden pegs mentioned above as a reference, it was possible to come back to measure the change in height of the same points in the plot after each tillage operation was performed.
- Aggregate size distribution. This was carried out in order to describe the loosening and crumbling after ploughing and harrowing, respectively. Measurements were concentrated in the layer from 0 to 10 cm. Just after ploughing, two samples for each experimental plot were taken. A metal frame of 0.5 m x 0.5 m was thrown at random, and all clods from inside were collected gently by hand down to 10 cm avoiding breaking. The relatively large size of clods after ploughing made collection easy. Then samples were transported carefully in plastic boxes to be air dried and sieved. For the characterization of the crumbling after harrowing, at each experimental unit, immediately after harrowing, five samples were taken at random, but avoiding wheel tracks. The aggregates were collected from two layers (0 to 4 cm and 4 to 8 cm depth) in order to characterize the

aggregate distribution at top layer and at the planting depth. The collection was made by placing a bottomless cake-tin at the desired depth. Samples were also transported carefully in plastic boxes to be air dried and sieved

3.2.1.2 Results and discussion: mechanical traction (tractors)

Soil condition before tillage operations

(i) Bulk density

Figure 8 shows the bulk density of the soils with depth. It can be seen that for the LOAM soil the density increases up to 20 cm depth then towards the 25 cm depth to a value similar to that found at 10 cm depth. The tillage history of the plots has been ploughing and harrowing with discs. Normally the ploughing depth is around 20 cm (the common practice in the region of study). It is thought that the increase of compaction up to 20 cm depth could be a plough pan.

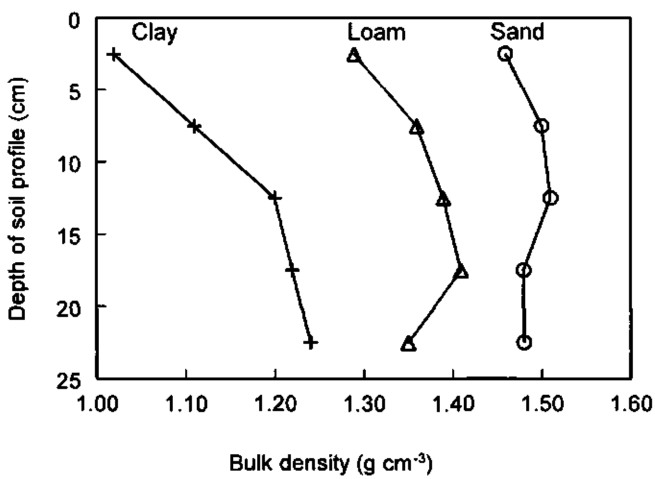


Fig. 8. *Bulk density before tillage.*

Tractor operators may perform tillage when the toplayer seems to be friable, but moisture content is still around the plastic limit at tillage depth (clay content increases below 15 cm depth). For the CLAY soil low values of bulk density were measured in the top layers, probably because of its relatively high organic matter content. Going down in the profile, the density increases as the organic matter content decreases (as shown in Table 3). Tillage in this soil has consisted of ploughing as well as harrowing with discs. For the SAND soil, the values do not change much in the profile with depth remaining at about 1.5 g cm^{-3}, which is a typical value of this soil texture.

(ii) Moisture content in the profile at the moment of tillage

Figure 9 shows the moisture content (MC) with depth at the moment that tillage operations were carried out on the LOAM soil. An attempt was made to perform tillage at moisture levels around the laboratory-determined plastic limit (PL) and the shrinkage limit (SL). Since for this soil these were 26% (w/w) and 18% (w/w) respectively, the soil was worked at MC in between (theoretical friable range) and outside these values.

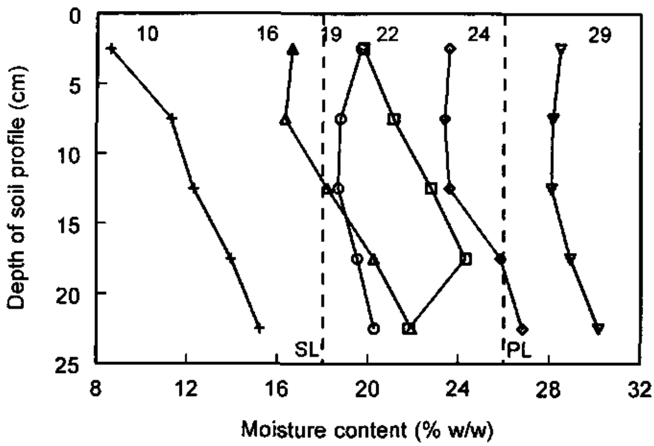


Fig. 9. *Soil moisture profiles during tillage for the* LOAM *soil.*

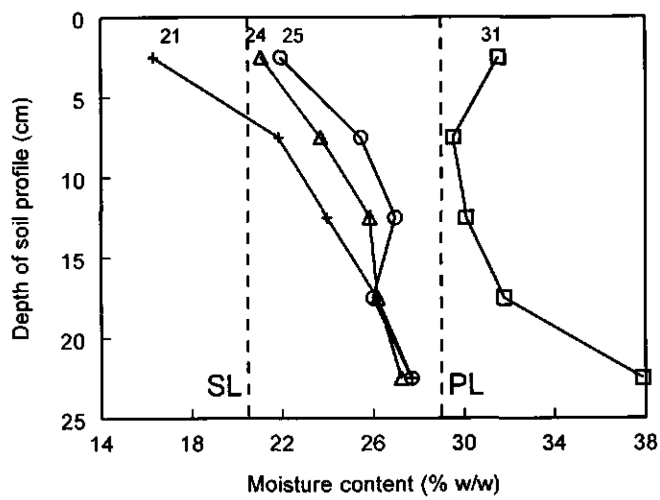


Fig. 10. *Soil moisture profiles during tillage for the* CLAY *soil.*

It can be seen that it is not possible to have a very uniform profile, since as the soil is drying out by evaporation, the top layers have always less water than the bottom ones. Thus the value shown at the top of each profile is the average, taking into account the working depth that was reached for ploughing.
Figure 10 shows the MC profiles for the CLAY soil. This soil is characterized by the slow movement of moisture in the profile so it is more difficult to keep water content uniform with depth. Since it was very obvious, due to trafficability problems, that tillage could not be performed when the top layer was wet, most operations were concentrated in the low friable range and below the SL. It can be seen that even if the moisture of the surface is around the SL, further down the soil is still moist. Thus, if surface moisture values were in the middle or toward the high end of the friable range (25 to 28 % w/w for this soil), the moisture content of the profile from 10 to 25 cm depth was very close to the PL. Only one moisture level was considered close to the PL.

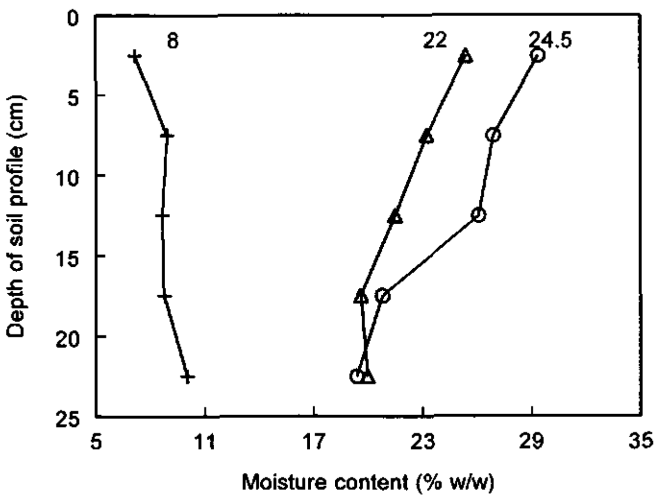


Fig. 11. *Soil moisture profiles for the* SAND *soil.*

Figure 11 shows the moisture of the soil profile when tillage was carried out at the SAND soil. The soil is regarded to have few workability problems because of its low clay content; a consistency-based lower plastic limit could not be determined.

(iii) Cone index

Figure 12 shows the profiles of cone index for the LOAM soil taken at different MC. The number at the top of each cone index profile is the average MC (cf. Figure 9). As expected, values depend on MC, but for the levels of 29% and 24% MC, there is an increase of cone index (CI) with depth, which confirms a dense layer at 20

cm depth. For the level of 22% the top layers were already drier than the bottom ones, so this is the reason for the CI seeming to decrease with depth.
The line of cone index at 19% MC increases sharply towards the 10 cm depth, as the moisture is going down to the SL. For the 16% MC there was little variation in the values of CI with depth. At the 10% MC it was not possible to measure the index (resistance too high).

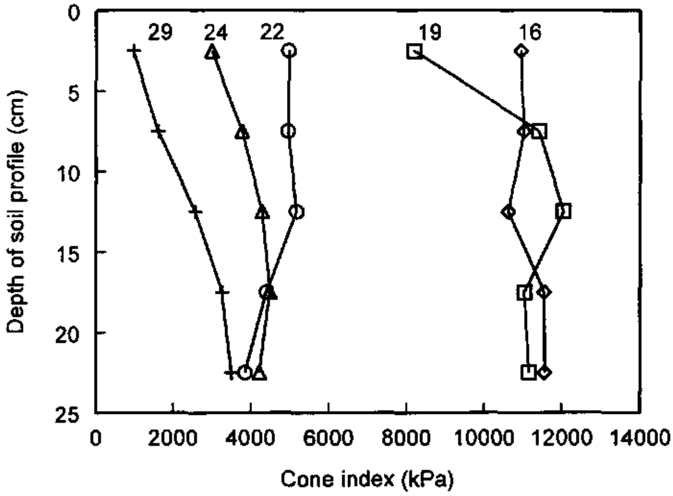


Fig. 12. *Profiles of cone index at each initial moisture content for the LOAM soil.*

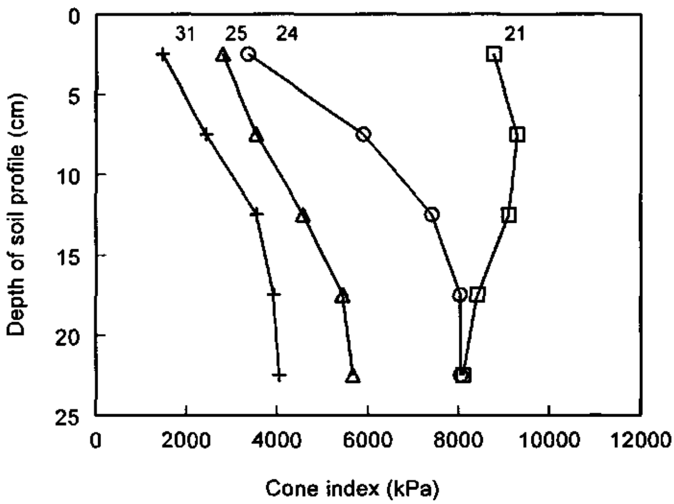


Fig. 13. *Profiles of cone index at each initial moisture content for the CLAY soil.*

The cone index profiles for the CLAY soil are shown in Figure 13. The values of cone resistance also depend on the moisture content. It is also observed that the resistance increases with depth more strongly than in LOAM, attributed to the stronger increase of the density of the soil with depth.
Figure 14 shows the cone index for the SAND soil. The same relation is found: cone index increases as soil moisture decreases.

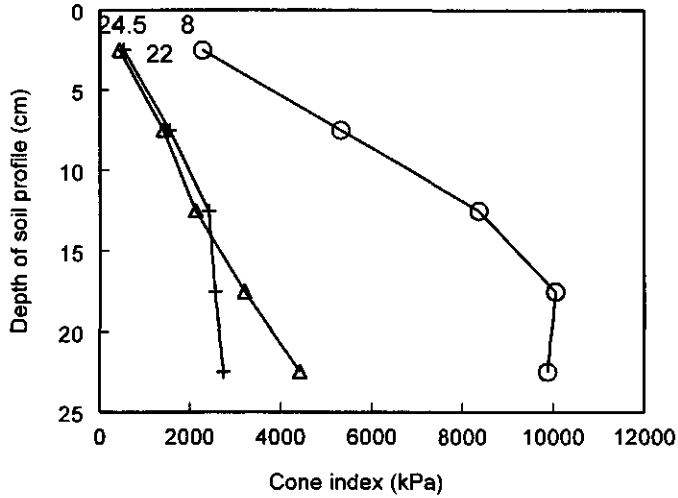


Fig. 14. *Profiles of cone index at each initial moisture content for the SAND soil.*

Soil condition after tillage operations
The resultant condition of soil after the tillage operation was the effect of the implement working at known initial conditions. The quantities used to characterize the result of tillage were working depth and upheaval, bulk density (after ploughing), surface roughness and aggregate size distribution (after harrowing). The most relevant varying initial condition was soil moisture content, so all resultant quantities were related to the initial moisture content. However in order to make comparisons among the soils studied (different textures and initial densities), soil water potential (pF) values were used in place of moisture content. Empirical relationships were made between the pF values and the quantities that characterize the tillage effect for LOAM and CLAY soils (the relevant soils). This was done in order to be able to relate optimum or sub-optimum quantities to matric potential thresholds, after the analysis of all field results. As references of the soil water potential around which change of results are expected, plastic limits (PL-L and PL-C) and shrinkage limits (SL-L and SL-C) for the LOAM and CLAY soils respectively, were used to indicate a theoretical friable range of these soils. No

relationships were developed for the SAND soil since quantities of tillage results were measured only when the soil was very dry, moist and very wet.

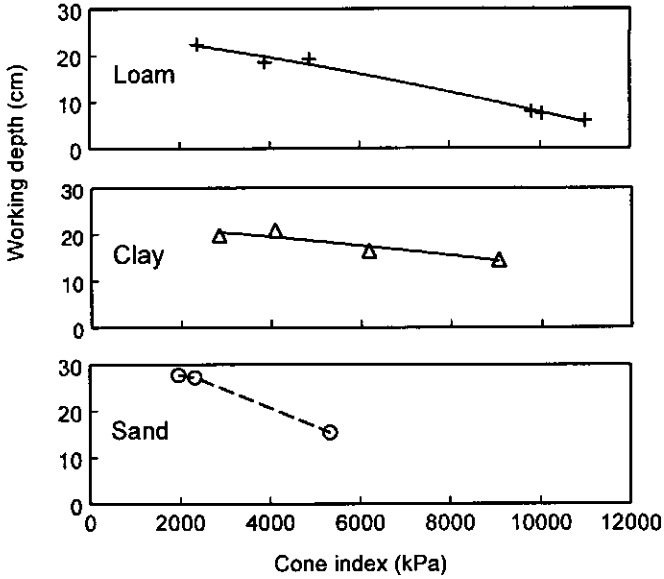


Fig. 15. *Relationship between working depth and cone index for the three soils.*

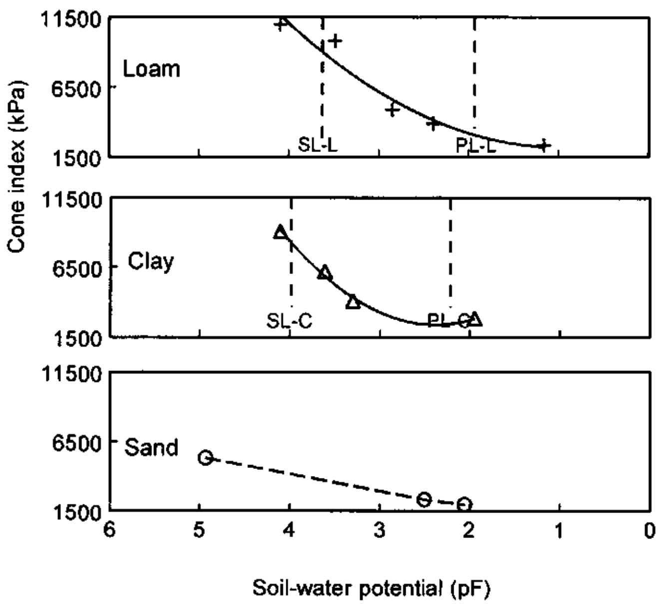


Fig. 16. *Relationship between soil-water potential and cone index.*

(i) Working depth and upheaval

For all soils and water contents, the plough settings were as follows. The discs' angles (vertical and horizontal) and the adjustment of the guide wheel in its position were set for maximum depth. However the penetration of the disc plough also relies on the weight of the implement, and no further arrangements were made (i.e. adding weight) to make the penetration of the implement in dry soil equal to that in moist soil, thus the penetration of the implement depends on the soil resistance.

Figure 15 shows how the working depth depended on the soil penetration resistance. In Figure 16, the relationship is presented between cone index and the soil water potential (pF). The suction value is plotted for each average moisture content of the soil profile against the average soil penetration resistance, both at working depth. As discussed earlier, penetration resistance depended on moisture content, thus working depth was shallow as the soil was drying out (Table 7).

A relationship is shown in Figure 17 between the soil water potential and working depth. In this figure, the empirical relationship for the LOAM and CLAY soil is represented by linear equations.

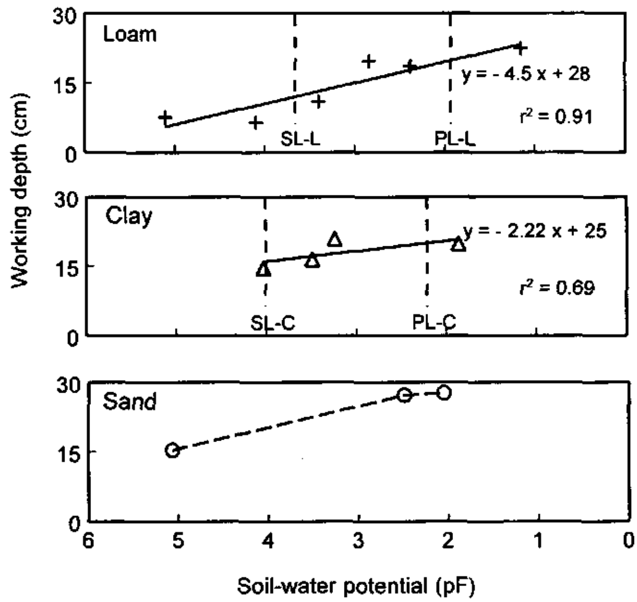


Fig. 17. *Relationship between soil water potential and working depth.*

In Figure 18 the upheaval is shown after the ploughing operation, and presented as a percentage of the working depth. A tendency of the upheaval to decrease in dry and wet soil for the LOAM and SAND soils has been noticed.

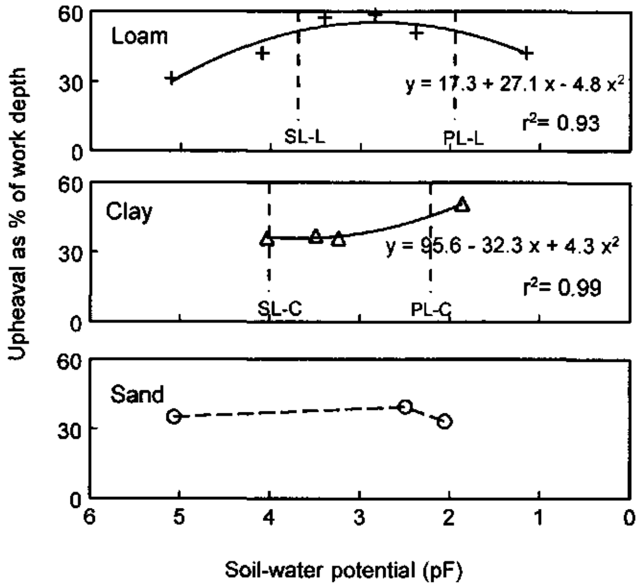


Fig. 18. *Relationship between soil-water potential and upheaval.*

For the CLAY soil the upheaval only increases as soil moisture increases in the range where this soil was tilled. The equations representing the empirical relationship for the LOAM and CLAY soils are presented in the graph. These relationships are important because the aim of ploughing is the loosening of soil and it is convenient to know, at which level of soil moisture more loosening is attained.

(ii) Bulk density and air filled porosity

Figure 19 shows bulk density values after ploughing. Taking as a reference the bulk density before tillage (Figure 8), the bulk density after tillage was calculated using working depth and upheaval. These data and the particle density of the soil were also used for the calculation of resultant air filled porosity. In general the reduction of density after tillage was around 30% of the initial value.

The air filled porosity after ploughing is shown in Figure 20. The tendency to decrease is due to the increase in water content, but the values are quite high (except for the very wet SAND soil). It is mentioned in the literature that air filled porosity below 10% is regarded as not good for crop establishment and root growth (Glinski and Lipiec, 1990; Dexter, 1996). No sub-optimum quantities of bulk density and/or air filled porosity were found at any moisture content after tillage.

After harrowing, a slight increase in density was noticed in the LOAM soil when working around the plastic limit, where the calculated bulk density was 1.0 g cm^{-3} compared with 0.93 calculated after ploughing. The air filled porosity only decreased approx. 5% (v/v).

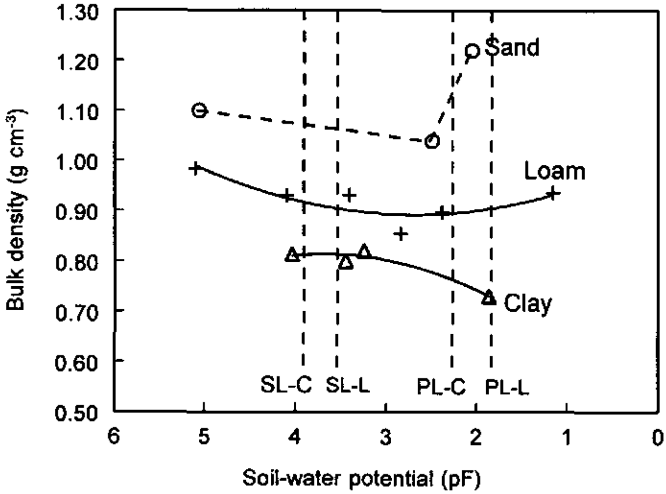


Fig. 19. *Calculated bulk density after disc ploughing.*

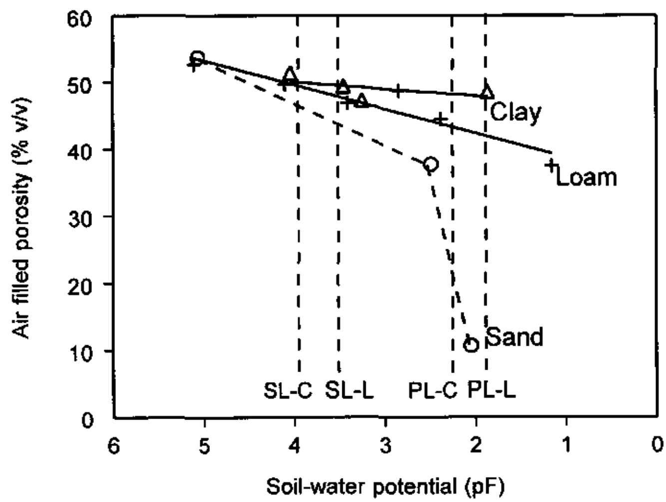


Fig. 20. *Calculated air filled porosity after disc ploughing.*

(iii) Surface roughness

Figure 21 shows the surface roughness after harrowing for the three soils. The roughness index is the standard deviation of the soil surface heights, expressed as the distance to the reliefmeter bar.

This index gives an indication of how suitable the surface was left after tillage for promoting infiltration, so was only calculated after the last operation. Figure 21 shows that the roughness index after harrowing ranges from about 2 cm for the SAND to around 5 cm for the CLAY. Steichen (1984) reports that in a field experiment in a silt loam soil (slope 1%) with a roughness index of 2 cm, the water depth that was infiltrated before runoff starts was more than double the index value (so > 4 cm). Depressional storage of rainfall and hydraulic resistance to overland flow are positively correlated with soil roughness.

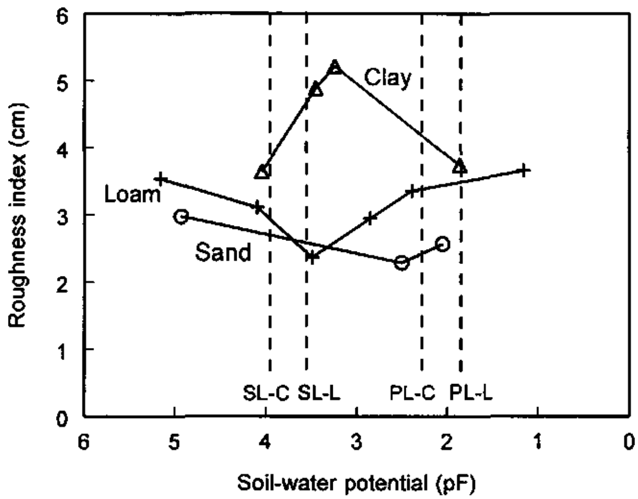


Fig. 21. *Roughness index of the surface after disc harrowing.*

In the WEPP project, Alberts et al. (1995) use average random roughness values assigned to each tillage implement as one of the factors to calculate values for the basic water erosion processes of infiltration and surface runoff. For example they assigned the value of 3.6 cm of random roughness after the disc offset harrowing operation. From the results in the present work this value more or less agrees with that for the LOAM (3.2 cm). SAND and CLAY have lower (2.6 cm) and higher (4.3 cm) values respectively.

From the figure it can be observed that roughness also depends on the initial water content of the soil, which influences the crumbling of surface aggregates. It was observed that harrowing the dry CLAY soil resulted in a smaller roughness index, the effect of the harrow was so slight that only few big clods were at the surface, giving the impression of an even surface when measured with the reliefmeter.

At any moisture content studied in this soils a coarse surface was left after completing the tillage operations. This is reflected as a roughness index greater than 2 cm. Thus, *in conclusion*, by performing conventional tillage with disc plough and disc harrow, a relatively high roughness index can be obtained at any moisture content, which is desirable when there is risk of erosion.

(iv) Aggregate size distribution

The aggregates in the seedbed after harrowing were sampled in two layers. This was done because there are conflicting requirements between the structure needed for prevention of soil erosion and that needed for a good germination. therefore it is necessary to stratify the tillage result and to compare it with the requirements in each situation.

(iv-a) Aggregate size at the surface after harrowing

Aggregates in the top layer (0-4 cm depth) need to be compared with those required to minimize soil erosion risk. From Figure 22 it can be seen that for the LOAM and CLAY, large aggregates with a mean weight diameter (MWD) greater than 20 mm, are found at the surface, with the exception of the LOAM just before the SL limit where the MWD is about 17 mm.

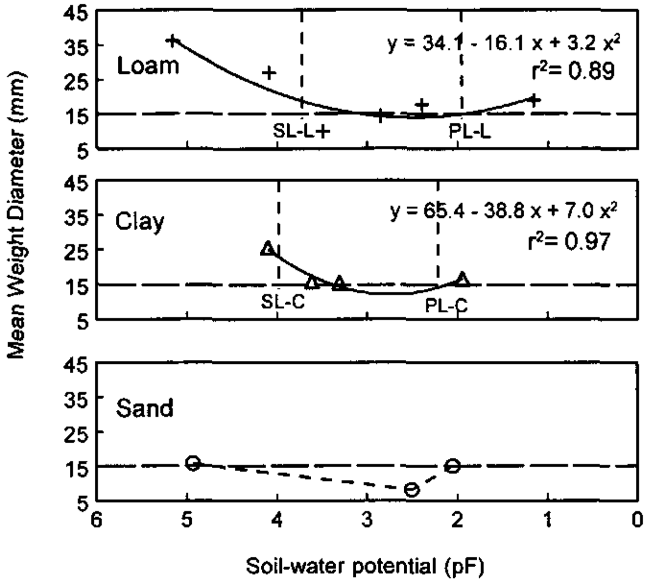


Fig. 22. *Size of aggregates (MWD) in the surface layer (0-4 cm) after disc harrowing.*

For the SAND large aggregates were found in the surface in very dry or very wet conditions.

Kritz (1976) reports that after tillage operations, large aggregates tend to be found near the surface. Although the aggregate stability is more important than the size with regard to soil erosion (Unger and Cassell, 1991), there is evidence that for different soil types a greater amount of soil is lost from small aggregates than from large ones, and that increasing the size of surface aggregates reduces breakdown and prolongs the time it takes to form a crust (Braunack and Dexter, 1989a). Cloddy surfaces provide depressions for temporary storage of water in the surface, which allows more time for infiltration, delaying or in some cases preventing the onset of runoff.

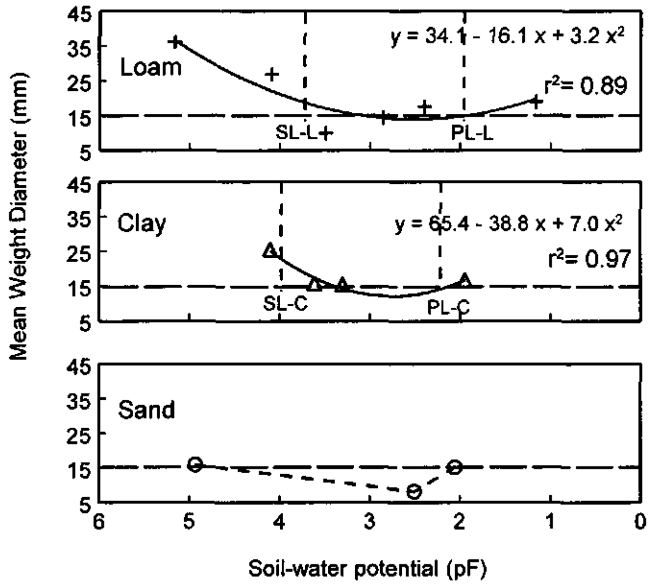


Fig. 23. *Size of aggregates (MWD) at planting depth layer (4-8 cm) after disc harrowing.*

(iv-b) Aggregate size at planting depth after harrowing

At this depth, the tendency is that the smallest MWD was produced at moisture levels around pF 2.5 (Figure 23). When drier, the aggregates are stronger, so is difficult to reduce its size and when wetter the aggregates are weaker and can be compacted and form larger ones. Tisdall and Adem (1988) in Australia, and Adam and Erbach (1992) and Wagner et al. (1992) in the USA have reported that larger aggregates are formed when performing tillage at both high and low moisture contents. For maize a suitable seedbed should have around 66% of aggregates

between 1 and 15 mm (Braunack and Mc Phee, 1991) the rest being either larger or smaller. The qualitative description of a good seedbed for maize given by farmers, extension workers and researchers in the area under study, agrees well with a resulting MWD smaller than 15 mm (Cadena et al., 1996). In Figure 23, the relationship between soil-water potential and MWD indicates that a MWD of maximum 15 mm results from working in the range between pF 1.9 and pF3.1, for the LOAM and between pF 2.1 and pF 3.4 for the CLAY.
After the analysis of variance (Annex 2) of the experiment in the LOAM, the F test indicates that in the whole experiment at this soil (no tillage and conventional tillage), the MWD variation is due to the significant effect of the soil moisture. Therefore in order to discover which are the differences in a specific tillage system, an additonal test has been carried out. A test was applied, calculating a least significant difference (LSD, $p< 0.01$) and performing a multiple comparison.

Table 5. *Mean weight diameter (MWD) at planting depth (4-8 cm) after the conventional tillage operations for each soil.*

Average water content at working depth		No tillage (MWD mm)	Conventional tillage (MWD mm)
(% w/w)	pF		
LOAM			
10	5.1	5.2 a	33.1 a
16	4	7.2 b	26.9 b
19	3.4	5.8 ab	9.9 c
22	2.8	5.5 a	14.3 d
24	2.3	4.5 a	17.7 e
29	1.1	6.4 ab	18.1 e
CLAY			
21	4	-	25.5
24	3.4	-	15.8
25	3.2	-	15.5
31	1.8	-	6.5
SAND			
8	5	-	15.8
22	2	-	8.2
24.5	1.4	-	15.5

Means with the same letter in a column are not significantly different ($p< 0.01$).

Table 5 shows the means of MWD for each tillage system. At the LOAM for the conventional tillage at different moisture contents a statistically different MWD is produced for the moisture values in the friable range and above the PL.

For the LOAM, the MWD's produced at the dry side below SL are not statistically different from each other. As mentioned earlier, no statistical design was used for the CLAY and SAND soils. Data of MWD for the no tillage system are plotted in Figure 24, where it can be seen that for this system there is no relationship between the size of the aggregates produced and the soil-water potential. The MWD's are quite low compared with those from conventional tillage.

To take this a step further, not only the MWD should be analysed but also the distribution produced at each moisture level, considering specifications for each crop.

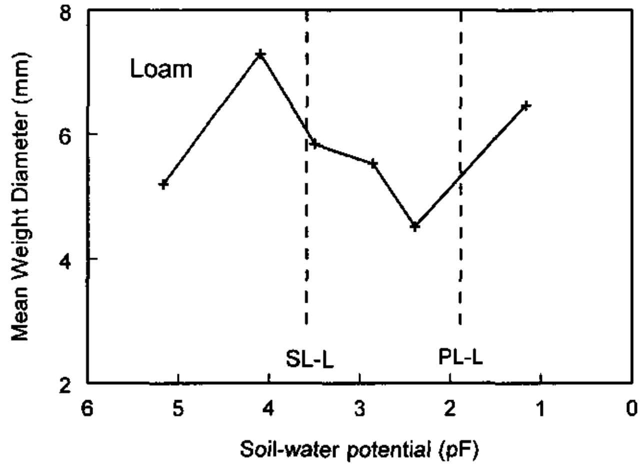


Fig. 24. *MWD of aggregates in and around the slot of no-till system for the* LOAM *soil.*

In Figures 25, 26 and 27, the distribution is shown (by selected classes) of the aggregates produced at the moisture contents studied at each soil (i.e. LOAM, CLAY and SAND, respectively).

According to the regression equation for the desirable class 2 to 16 mm (Figure 25, LOAM), the maximum amount (about 44%) of this size class will be produced when working between pF 2 to pF 3. Thus working soil with a MC outside of this range obtains sub-optimum results in terms of aggregates at planting depth. The production of big aggregates (> 16 mm) is increasing sharply as the soil dries out. But also when working above the plastic limit (PL). The production of fine aggregates (< 2 mm) follows just the opposite trend observed for the coarse ones. The range of soil-water potentials within which the highest percentage of aggregates in the class 2 to 16 mm is produced, is just slightly smaller than that shown in Figure 23 where MWD of maximum around 15 mm, results from working between pF 1.9 and pF 3.1.Thus for this soil, it could be concluded that using conventional tillage a good product of the tillage operations for maize establishment in the area under study will be attained between pF 2 and pF 3.

For the CLAY soil, according to the relationship between the soil-water potential and the amount of aggregates produced, it can be observed in Figure 26 that also the highest amount (around 42 %) of aggregates class 2 to 16 mm results from working between pF 2 and pF 3.2.

Figure 23 showed that for the CLAY soil, the MWD of maximum 15 mm is produced between pF 2.1 and pF 3.4. This also rather well agrees with the suction range where the highest percentage of aggregates class 2 to 16 mm are obtained.

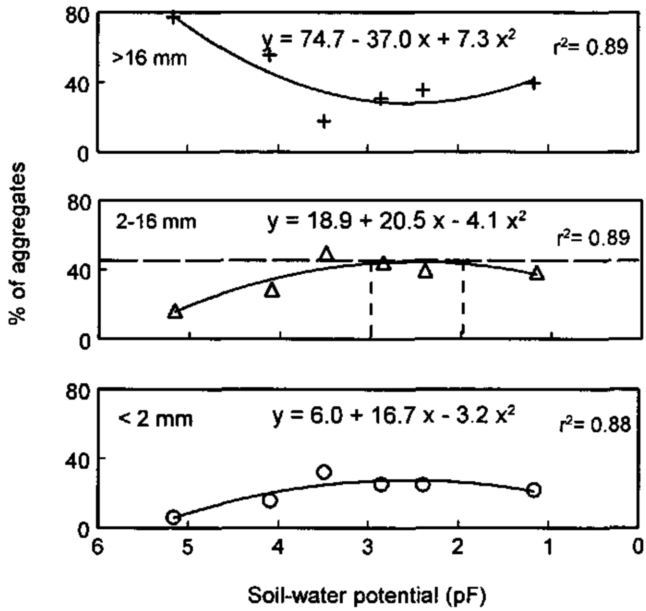


Fig. 25. *Distribution of aggregates by size ranges at planting depth after disc harrowing for the LOAM soil.*

For the SAND soil, the points are shown in Figure 27. For this soil, the production of aggregates class 2 to 16 mm is increasing as moisture content goes up. When working this soil, the resulting MWD, at any matric potential, will be close to or under 15 mm (Figure 23). From the graphs in Figure 27, for this soil the best distribution of aggregates would be achieved at soil-water potential pF 2 to pF 2.3

Conclusion: for conventional tillage (ploughing and harrowing), the optimum moisture range (for the best technological result) is between pF 1.9 and pF 3.1 for the LOAM soil and between pF 2.1 to pF 3.4 for the CLAY soil. At this suction ranges a maximum MWD of 15 mm is produced which implies the highest percentage of aggregates in the class 2 to 16 mm.

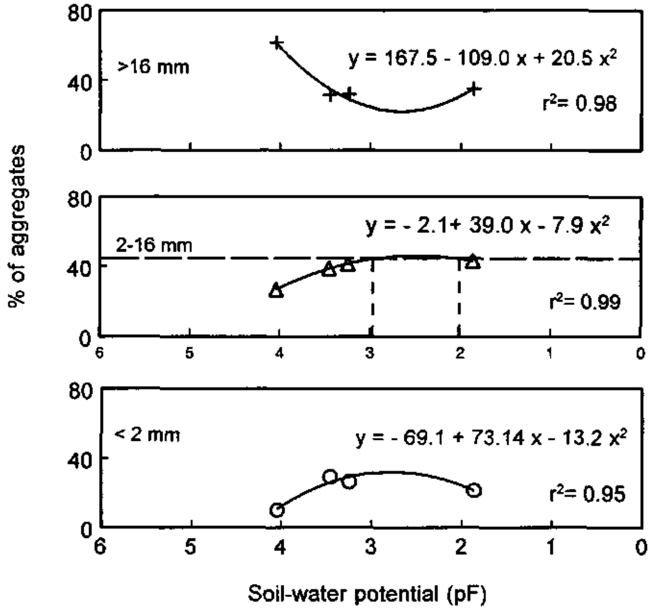


Fig. 26. *Distribution of aggregates by size ranges at planting depth after disc harrowing for the* CLAY *soil.*

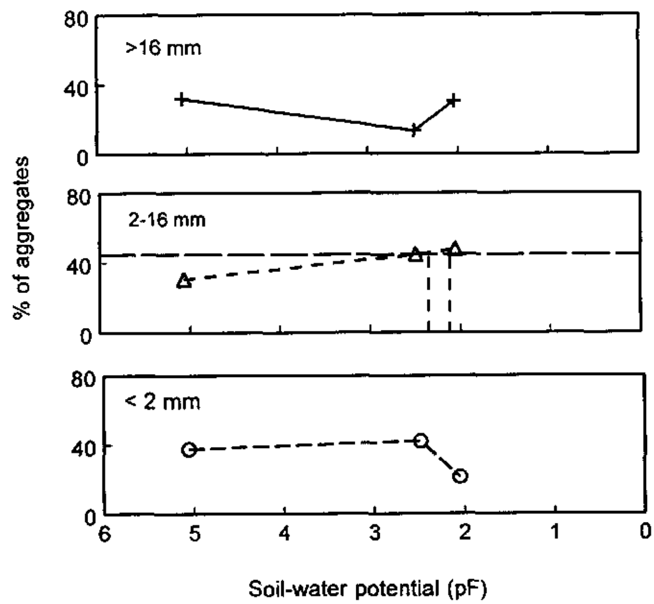


Fig. 27. *Distribution of aggregates by size ranges at planting depth after harrowing for the* SAND *soil.*

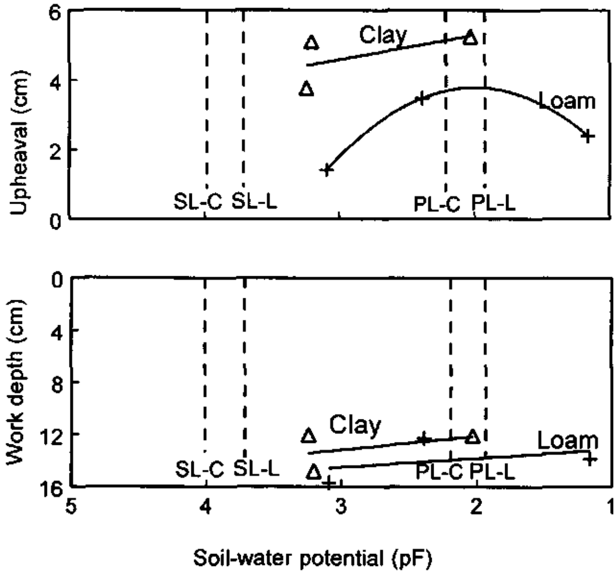


Fig. 28. *Working depth and upheaval after mouldboard ploughing with animal traction.*

For the SAND soil, the technological result (MWD of 15 mm) would be attained at almost any moisture content, but the best distribution of aggregate sizes would be achieved between pF 2.1 and pF 2.3.

Regarding the no tillage experiment performed in the LOAM soil, Figure 24 showed that a positive effect of the soil engaging components of the no-till planter can be expected at any moisture content in the range where experiments were carried out. Thus, the decision as to whether to carry out the operation depends more heavily on the trafficability of the soil in a wetter condition and adequate moisture content for seed germination as soil dries out.

The information from the field experiments answers the question of when the required technological effect of tillage can be achieved for the area under study.

3.2.1.3 Results and discussion: animal traction

Soil conditions after tillage (mouldboard ploughing)

(i) Working depth and upheaval

Figure 28 shows the working depth and upheaval for the LOAM and CLAY soils. It can be observed that working depth and upheaval do not change much within the range of moisture content at which those soils were tilled. The range of soil moisture at which animals can work is quite narrow, and this was chosen by the trainer of the animals. He based his judgement on the difficulties presented by walking in the field with the animals, and the effort needed for performing the tillage operation. The working depth was from about 13 to 15 cm. Upheaval increases slightly in more friable soil, compared with the values in drier or wetter situations. This is an indication of where the loosening of soil may be better attained. The animals cannot work in dry soil; the lowest moisture content at which tillage can be performed is well above the shrinkage limit.

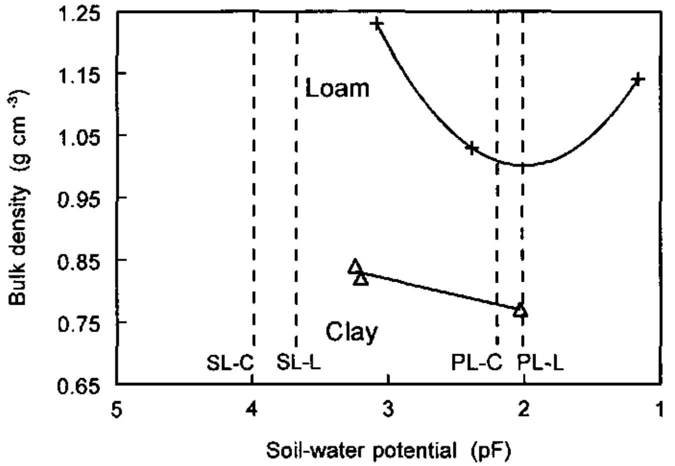


Fig. 29. *Calculated bulk density after mouldboard ploughing with animal traction.*

(ii) <u>Bulk density and air filled porosity</u>

In Figure 29, the bulk density after the soil loosening with the mouldboard plough is shown. For the LOAM soil better work is achieved just below the plastic limit, while for the CLAY soil better loosening is attained as the soil-water potential decreases (increase in soil moisture). For both soils, the highest decrease in bulk density was achieved around the plastic limit. In Figure 30 the air filled porosity is shown. For the LOAM soil, the value of porosity merely follows the increase in upheaval, and thus follows the decrease in bulk density. Not much change is observed for the CLAY soil.

(iii) <u>Mean weight diameter</u>

For the LOAM soil the values of the MWD do not change much at different soil water potentials. The MWD of the CLAY soil has a tendency to decrease as moisture content increases (Figure 31). The MWD is just the result of mouldboard ploughing only. Relatively smaller aggregates result at soil water-potentials around pF 2 for both soils. No additional operations were carried out. The technological result of tillage is secondary, since the crop is planted normally by hand and for small areas (up to 2 ha) a good soil-seed contact is achieved by pressing soil around the seed by foot.

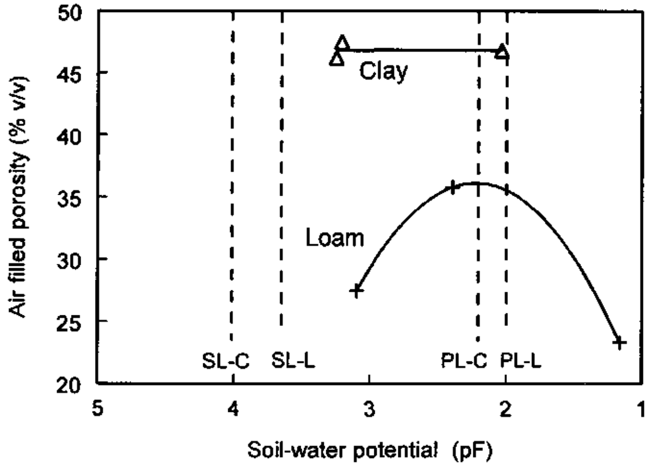


Fig. 30. *Calculated air filled porosity after mouldboard ploughing with animal traction.*

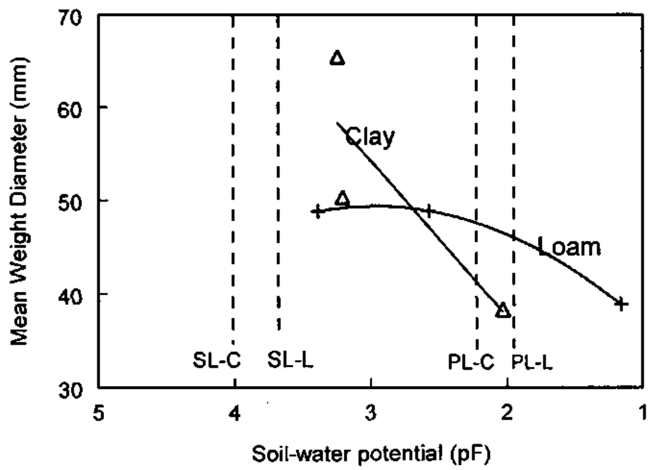


Fig. 31. *MWD after mouldboard ploughing with animal traction.*

In conclusion: for animal traction the important effect is the loosening of the soil, which is properly achieved in a very narrow range of soil-water potential, this being chosen by the animal operators. This means that they must plough in the friable state of the soil. Because of the limited power of the animals, the farmers/operators obey the criteria of energy demanded when deciding for tillage.

3.2.2 Field studies on energy aspects

3.2.2.1 Materials and methods

Information on the soils, power sources and implements is presented in Chapter 3.2.1.1; the tillage system applied, and the soil conditions during the tests (moisture contents, densities) are described in Chapter 3.1.3.1.

The following data were collected in the field with respect to tillage with a tractor at each experimental plot:

- Fuel consumption in the field. A fuel consumption meter was incorporated in the fuel system of the tractor. This device has two sensors: one measuring the flow going into the fuel injection pump, and another one measuring the flow in the return line to the fuel tank. A screen displays the net amount of fuel used by the engine. For ploughing, fuel consumption was measured using the 4th forward gear of the tractor, keeping the engine speed constant at 1600 rpm. Two runs for each experimental plot (5 x 50 m) were made with the implement lifted (to measure rolling resistance) and six runs performing the operation. For harrowing, the 5th forward gear with an engine speed of 1500 rpm was used, and because of the larger working width, only two runs were made performing the operation per experimental plot. One run was made in the ploughed field with the implement lifted.
- Time. The time for travelling the 50 m (same runs as above) was measured in order to obtain the fuel consumption rate.
- Working speed. In order to calculate the working speed, the time for travelling 20 m was measured for each run (six replications for ploughing and two for harrowing).
- Working depth. Working depth was measured four times at each run, yielding 24 measurements for each experimental plot for the ploughing. For the harrowing, the working depth was measured next to the tines when the tractor was stopped, without lifting the implement.
- Working width. Working width was measured each run by placing a peg at the border of the tilled strip as a reference. Six measurements were taken for ploughing and two for harrowing at each experimental plot.

The following measurements were made in the laboratory:

- A standard PTO test facility was used to establish a relationship between the power delivered by the tractor and fuel consumption. In this facility, the instrumentation measures PTO power and torque, engine and PTO speed, fuel consumption, and temperatures of the engine oil, transmission oil, coolant and exhaust. Fuel consumption and power were measured keeping the engine speed constant and varying the load. The results of this test were used to obtain the power used in the field.

Calculation of energy applied for tillage operations.
Implement specific energy applied in the field was determined as follows:
$E = P / (G/s)$ where:

- E = specific energy ($J\ kg^{-1}$)
- P = the net power used for the tillage operation (kW)
- G/s = weight of the soil moved per second by the implement ($kg\ s^{-1}$)

In the field, apart from fuel consumption, also slippage was measured. Via the PTO test, the equivalent PTO output was calculated.
The net power (P) used in the tillage operation is the amount left from the total, after subtracting that used for rolling resistance and for slippage. This power (P) to pull the implement, then can be expressed in $J\ s^{-1}$.
The weight of the soil moved by the implement per second (G/s) is calculated by multiplying working width, depth and forward speed by the bulk density of the soil.
Data collection for tillage with animal traction at each experimental plot.
Prior to each run, the same sort of initial conditions were determined as for the tractor experiments.
Working width and speed were measured 6 times, working depth 24 times, and force to pull the implement was measured by a force transducer at intervals of about 5 m while working continuously (in a working distance of 120 m). All measurements were made at each experimental plot.

3.2.2.2 Results and discussion: mechanical traction (tractors)

<u>(i) Calibration</u>
Figure 32 shows the relationship between fuel consumption and power delivered in the laboratory for the engine speeds used in the field. Second order polynomial regression equations are used to predict PTO power from fuel consumption.
The regression equations were used to predict the power (kW) demanded in the field as described earlier.
When performing the PTO test, the fuel consumption meter used in the field was also used in the laboratory to compare with the measurements of the (much more sophisticated) test apparatus. The field measurements were corrected based on this comparison.

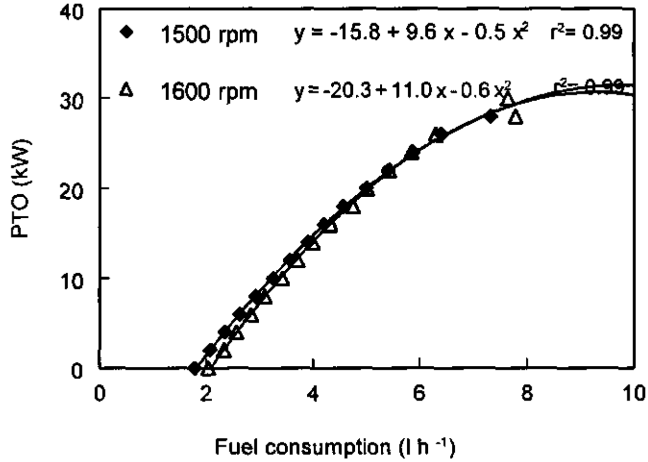


Fig. 32. *Relationship between fuel consumption and power at PTO in the laboratory.*

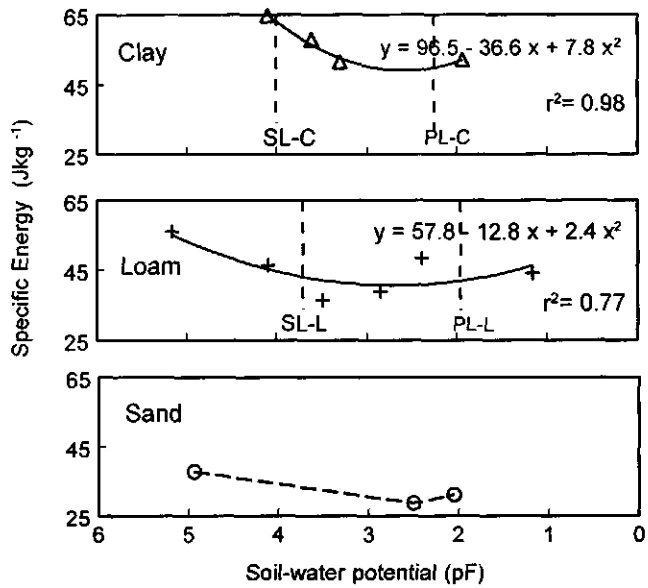


Fig. 33. *Specific energy applied for disc ploughing.*

(ii) <u>Energy expenditure for field operations</u>

Ploughing

Figure 33 shows the specific energy applied for the loosening operation with the disc plough for each soil. Although different working depths were reached at different moisture levels of soil, the calculation of specific energy allows comparisons. For all soils, the specific energy shows a minimum between SL and PL. The amount of energy needed at any soil water potential, becomes bigger according to the clay content of each soil.

In Figure 33 it can be seen from the data points that the lowest amount of energy applied for loosening the soil is in the range from pF 2.8 to pF 3.4 for LOAM, and from pF 2 to pF 3.3 for CLAY. Therefore this will be the optimum range of soil-water potential for soil loosening. This range agrees well with that for the maximum upheaval (Figure 18) for LOAM. For CLAY high values of upheaval were attained near pF 2.0.

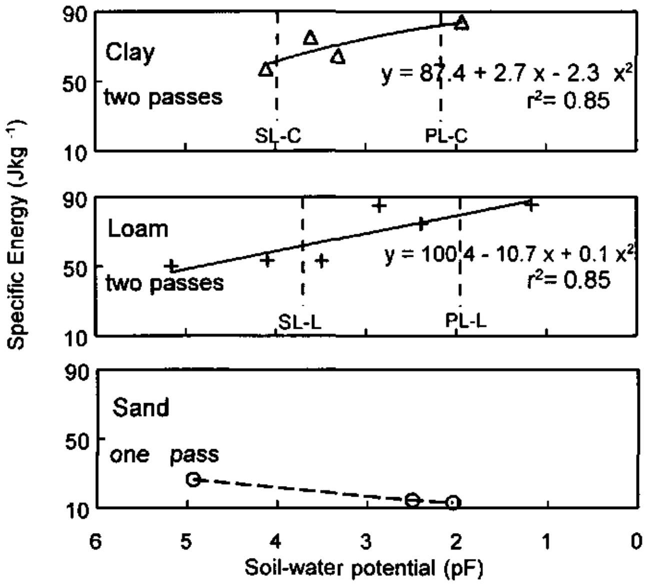


Fig. 34. *Specific energy applied for disc harrowing.*

Harrowing

Figure 34 shows the relationship between the moisture content and the specific energy applied for harrowing. Note that for CLAY and LOAM two passes were necessary to obtain satisfactory results. No relationship was established for SAND since data were collected at the extreme moisture contents only.

For SAND, only one pass of the harrow was made. For LOAM and CLAY, it can be seen that the lowest amount of energy applied is in the dry range and at the beginning of the friable range. In a dry soil little work is done and the technological result of tillage is a poor seedbed quality (Figure 23).

Figure 34 shows that specific energy increases as moisture content increases.

This is because when harrowing dry soil, both the work of cutting done by the discs and the working depth are small, and only some dust can be detached from the hard clods by the disc. This results in a low energy input, as well as poor results in terms of seedbed quality. At higher moisture contents, the soil becomes friable and more cutting is done by the discs, who will work deeper as more desegregation is obtained by shattering. Thus more work is done and the demand of energy increases. More energy is also needed to pull the discs through friable and wet soil. In dry soil, only friction causes resistance when discs are passing through the soil at shallow depths. As the soil is getting moist, adhesion begins and increases at the interface between soil and steel so resistance to the discs is greater.

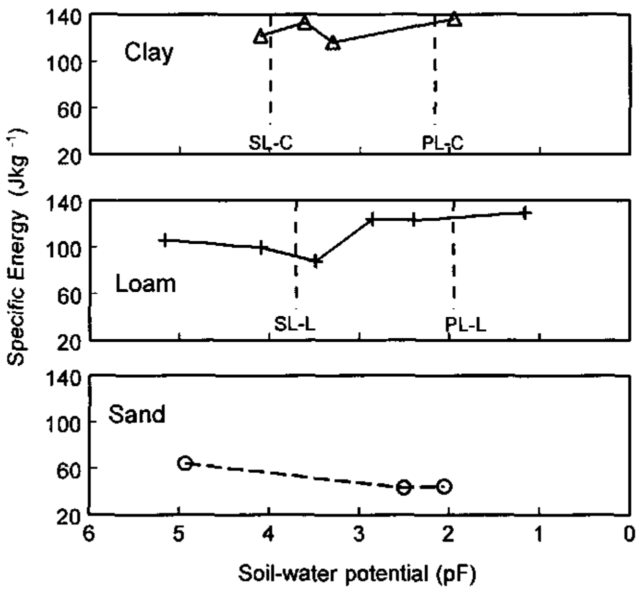


Fig. 35. *Total specific energy applied for conventional tillage.*

For CLAY the higher values of energy compared with LOAM are due to a higher resistance by adhesion forces in the interface between soil and steel because of the high clay content of the soil (between 50 and 57% compared to 26 - 30% for LOAM at working depth).
Considering the energy applied for harrowing the SAND, in this case the energy expenditure decreases as the soil water content increases. This is because the sand content is quite high (about 47%) so when dry, frictional forces are high, and there is high resistance to the pass of the discs. When the moisture content increases, friction diminishes because water acts as a lubricant.
Two harrowings of LOAM at pF 3.1 (the dry boundary of the optimum range as

increases, friction diminishes because water acts as a lubricant.
Two harrowings of LOAM at pF 3.1 (the dry boundary of the optimum range as shown in Figure 23) would require 67.6 J kg^{-1} (Figure 34) in order to produce a seedbed with an MWD of 15 mm. At the wet boundary (pF 1.9) 80.2 J kg^{-1} would be required.
Similarly for CLAY, if pF 3.4 is the driest limit, 69.8 J kg^{-1} have been applied to obtain 15 mm MWD and 82.8 J kg^{-1} were applied at pF 2.1 as the 'wet' threshold for optimum results.
Figure 35 shows the total specific energy (without taking into account working depth) applied for conventional tillage for CLAY, LOAM (disc plough and two harrowing) and SAND (disc plough and one harrowing).
The lowest amount of total specific energy applied after the operations was at pF 3.3 for CLAY: this is almost in the dry boundary (pF 3.4) where the final result of tillage gives a MWD of 15 mm (Figure 23). For LOAM it was at about pF 3.4 which is a moisture content slightly below the boundary (pF 3.1) to produce a 15 mm MWD as shown again in Figure 23. For SAND the lowest total specific energy was applied at pF 2.5.

Table 7. *Total energy applied (kWh ha^{-1}) after tillage operations for each soil.*

Average water content at working depth		No tillage		Conventional tillage	
(% w/w)	pF	Energy (kWh ha^{-1})	Working depth (cm)	Energy (kWh ha^{-1})	Working depth (cm)
LOAM soil					
10	5.1	1.8 a	5.2	68.9 a	7.6
16	4.0	1.9 a	5.2	55.2 b	6.5
19	3.4	2.1 a	5.6	61.7 c	11.0
22	2.8	2.1 a	5.0	124.5 d	19.7
24	2.3	3.4 b	5.5	132.0 e	18.6
29	1.1	4.2 c	6.4	148.1 f	22.4
CLAY soil					
21	4.0		-	93.0	
24	3.4		-	123.3	
25	3.2		-	114.9	
31	1.8		-	132.2	
SAND soil					
8	5		-	64.5	
22	2.5		-	103.0	
24.5	2.0		-	113.5	

Means with the same letter in a column are not significantly different ($p< 0.01$)

Table 7 shows total energy spent (expressed in kWh ha^{-1}) at each moisture content. This energy was calculated taking into account the working depth. As

For LOAM in conventional tillage, almost doubling the working depth (from 11 to 19.7 cm) doubles also the energy spent (61 to 124 kWh ha^{-1}). In relation to the no-tillage system, the working depth and the related energy does not vary much with moisture content.

In conclusion: on application of energy with tractors, the best option would be to perform a shallow ploughing (between 10 and 15 cm) at about the dry boundary where a 15 mm MWD (adequate size of aggregates at planting depth) results for CLAY and LOAM (pF 3.3 and pF 3.1 respectively). For SAND the shallow ploughing should be carried out at pF 2.5.

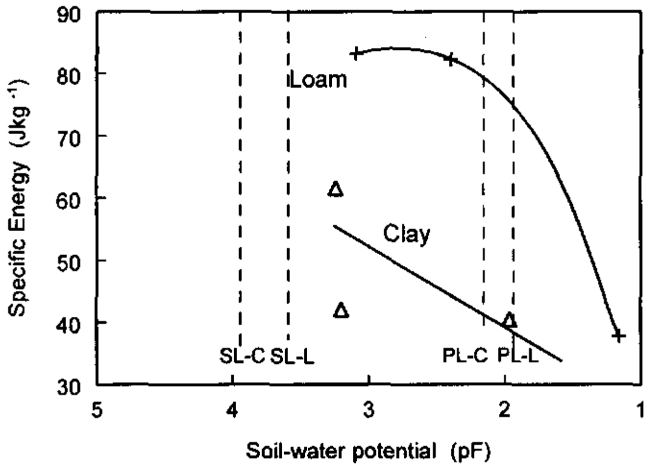


Fig. 36. *Specific energy applied for mouldboard ploughing with animal traction.*

3.2.2.3 Results and discussion: animal traction

Energy for ploughing

Figure 36 shows the specific energy applied for ploughing with animal traction at different moisture contents. It can be seen that for LOAM, a considerable decrement is taking place above PL. For animal traction, workability limits will be set taking into account mainly the demand of energy. The optimum workable range for animal traction is very narrow, in the friable range just below PL about pF 2 for LOAM and about pF 2.3 for CLAY as can be seen in Figure 36.

In conclusion: for animal traction, it is clear that the farmer/operator is always working in the friable range close to the PL, where good results are produced with a relatively lower demand of energy. There is not much choice, due to the low availability of power from the animals.

3.2.3 Developing and validating laboratory tests for workability criteria

3.2.3.1 Introduction

The application of a laboratory method (as simple as possible) to assess the field workability criteria is tested. If a reliable relationship between laboratory results and field experiments is found, it is possible to determine the workable range for other soils in the area just from this laboratory test.
For the determination in the laboratory of a wet workability limit, it was decided to validate the air permeability tests and the Moisture Pressure Volume diagram (MPV). In the air permeability test, a known volume of air will pass under a known air pressure through a prepared soil sample. The wet workability limit (WWL) is considered at the moisture content where after compressing a sample at 4 bars, the resultant air permeability is 1 $*10^{-12}$ m^2 (Perdok and Hendrikse, 1982)
The MPV diagram is a curve expressing the resulting pore space (V) vs. the moisture content (M) at quick uniaxial compaction with a given pressure "P" (Lerink 1994). The curves in a MPV diagram are denoted as isobars, and can be divided in two parts: the descending part of the isobar which is called the 'dry limb.' and the rising part which is called the 'wet limb'. Compaction processes at the 'dry' part are defined as strength hardening, at the 'wet' part these can be defined as flow processes. In the transition zone, near the bending point, both processes occur simultaneously. Just before the bending point, coming from the 'dry' part is the position where a wet workability limit can be set, since the beginning of flow processes means soil structure damage.
For a dry workability limit, the design of a laboratory drop test was considered, according to the work of Bernsten and Berre (1992), Hadas and Wolf (1984) and Watts et al. (1995a). It consists of measuring the kinetic energy of a falling weight, which is transferred for the fragmentation of a soil clod and to determine the aggregate size distribution obtained. The amount of energy and the resultant size of aggregates will depend on the initial conditions of soil moisture, mass and height of aggregate. The aim of the test is to assess how, and to what extent the technological effect of crumbling (soil desegregation) is attained by applying different amounts of energy to a soil at different moisture contents. With decreasing moisture content, there is a point at which the quality of the work required (in terms of aggregate size) is not being attained anymore.

3.2.3.2 Materials and methods

(i) <u>Air Permeability Test</u>
A sample is prepared by completely filling a 100 cm^3 steel cylinder with soil

particles graded in the fraction 2.8 to 4.0 mm (a mass of approx. 80 g). The sample is steadily compressed top-down (by means of a manual or automatic press) until pressure reaches 4 bars. The height of the sample after compression is calculated by measuring the distance from top of the cylinder to the compressed soil with a micrometer after the soil rebound. After that, the air permeability is measured by means of an air permeameter (Figure 37).
The air permeability is calculated as follows, Kmoch (1962).
$Ka = V \eta L t^{-1} A^{-1} P^{-1}$ where:

- Ka = intrinsic permeability by air flow (cm^2)
- V = volume of air (cm^3)
- η = viscosity of air (dyne s cm^{-2})
- L = length of sample (cm)
- t = time for volume of air, to flow through the sample (s)
- A = cross-sectional area of the sample (cm^2)
- P = air pressure (dyne cm^{-2})

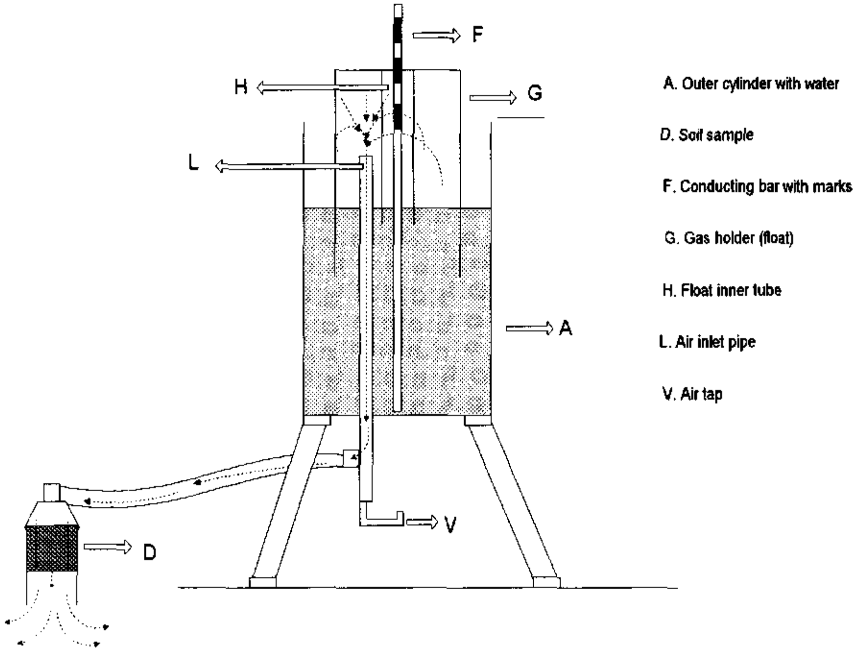


Fig. 37. *Air permeameter model IMAG (after Perdok and Hendrikse, 1982).*

(ii) <u>Moisture Pressure Volume (MPV) diagram</u>
Soil material is graded in the range of 2.8 to 4 mm, then samples of pre-defined moisture contents are prepared by carefully drying or wetting the aggregates (time for equilibrium of moisture in the sample needs to be allowed). A set of 5 cylinders

of 100 cm^3 is filled with soil of one of the pre-defined moisture contents and weighed. Each cylinder is steadily compressed top-down up to a pre-defined load (i.e. 50, 100, 200, 400, 800 kPa) by a press. After compression, the final height of the soil in the cylinder is measured, then the cylinder is put in an oven for 24 h at 105°C to obtain the dry weight of soil. Pore space is calculated from the resultant bulk density and the soil particle density. Then an MPV diagram (cf. Figures 40 and 41) can be made.

(iii) Drop test

The test apparatus is a steel box with the dimensions 360 mm x 260 mm x 150 mm, with a pipe connector at the top, to fix a PVC pipe vertical to the centre of the steel box. The PVC pipe is 101 mm in diameter and 1000 mm in length and has four rows of five holes 25mm in diameter, to reduce any problem of air resistance when dropping an object through it. The pipe can slide to allow placement of a soil clod in the box.

The cylindrical weights to be dropped are of 2.6 kg (steel) and 0.6 kg (wood) mass, each with a diameter of 99 mm. A drawing of the apparatus is shown in Figure 38.

The procedure for the drop test is as follows: a clod is weighed, then placed at the centre of the bottom of the steel box. Then with a caliper, the distance (h1) is measured from the top of the clod to the top of the steel box, where the PVC pipe is placed. The weight is allowed to fall from the top edge of the PVC pipe, so the sum of h1 and the length of the PVC pipe (h2) equals the dropping height. After the drop, the shattered aggregate resulting from the impact is collected carefully and put in a small aluminium tray, which is placed in the oven for 24 h at 105°C, in order to calculate the moisture content. Then the soil is passed through the same set of sieves used for the soil from the field experiments, and the MWD is determined.

Since only one length (1000 mm) of PVC pipe is used, the energy applied for one weight is about the same, so any variation in specific energy is only due to the size of the original aggregate, which influences h1. The specific energy applied will vary, because it is obtained by dividing the energy applied by the dry mass of the clod, thus it will vary due to the weight of the clod (Watts et al., 1996a):

$E = (mg \cdot (h1+h2)) / G$ where:

E	= specific energy (J kg^{-1})
g	= acceleration due to gravity (m s^{-2})
m	= mass of falling weight (kg)
h1	= distance from top of clod to top of steel box (m)
h2	= length of guiding PVC pipe (m)
G	= weight of clod (kg)

In this particular situation under study, the final size of aggregates for the seedbed is that produced by the disc harrow, which is used after the disc plough has loosened the soil. The study is focussed on the fragmentation of clods, beginning with the size left after the soil loosening by disc plough. In the field, the MWD of clods in the soil surface after ploughing was from about 50 to 60 mm in the dry and friable moisture levels. The ten (visually) biggest clods after loosening at each level, were also measured and found range from about 80 up to 200 mm. The use of similar sizes was also considered for the test.

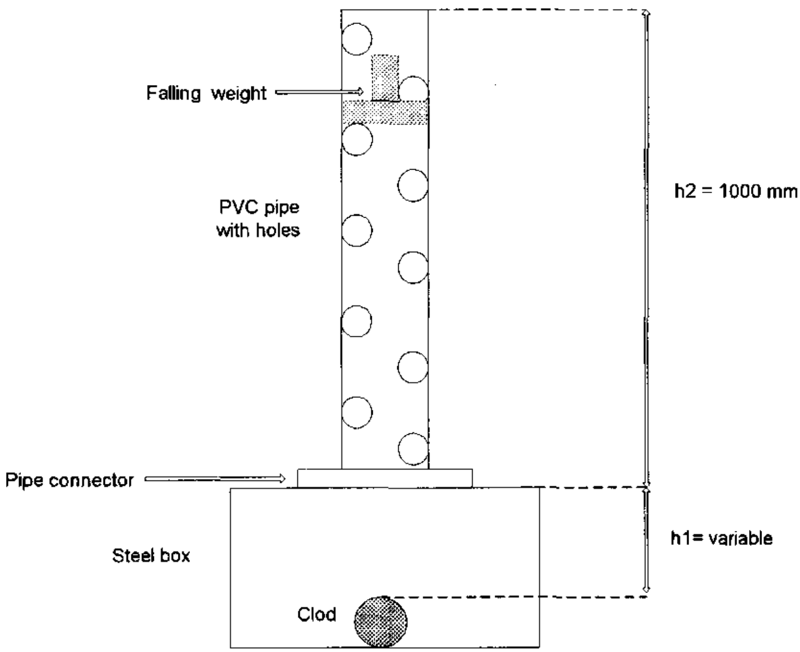


Fig. 38. *Apparatus for performing the drop test.*

It was found after preliminary tests with clods produced in the laboratory, that an adequate representation of the process could not be constructed. It was therefore decided to use natural aggregates, just as they are produced in the field after ploughing. Aggregates were collected carefully after loosening the soil, transported in a box and immediately processed as one batch with the same moisture content.

3.2.3.3 Results and discussion

(i) Wet workability limit (Air Permeability test)
Figure 39 shows the results of the air permeability tests. A regression equation

has been calculated for the best fit of the points for LOAM. From this, the corresponding soil-water potential for an air permeability of $1*10^{-12}$ m^2 is at pF 2.0, which is quite close to the PL (pF 1.9). According to the results of the field experiment, this value could represent a wet workability limit for this soil, considering that suboptimum results in terms of the MWD of aggregates begin to appear at around pF 1.9 as the soil moisture increases.

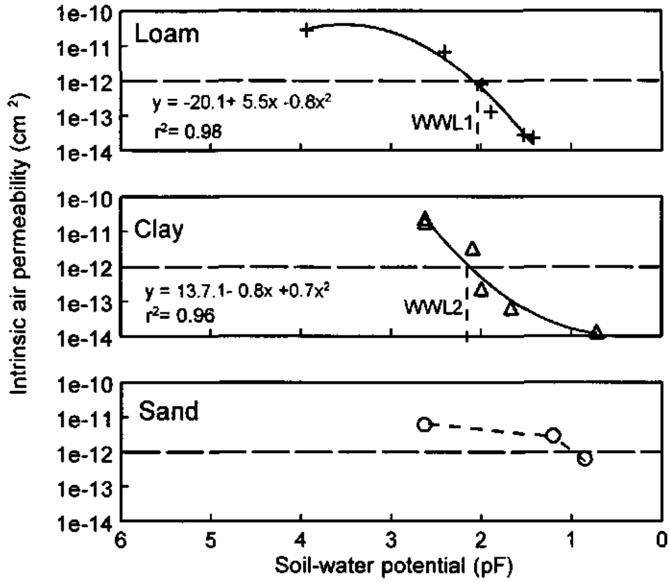


Fig. 39. *Wet workability limit (WWL) determined by the air permeability test.*

For CLAY the corresponding soil-water potential for the $1*10^{-12}$ m^2 of air permeability is pF 2.1, calculated by using the equation which best fit the data. This is also very close to the PL (pF 2.2). Also, according to the field results on work quality for this soil, when moisture content is increasing, suboptimum results in terms of the MWD begin to appear at soil water potential pF 2.1.

In relation to SAND, Figure 39 also shows a graph with some points that indicate a WWL for this soil. At that point the soil would be very wet (about pF 1), and energy aspects prevail as criteria for a 'wet' threshold.

(ii) <u>Wet Workability Limit (MPV diagram)</u>

Figures 40 and 41 show the MPV diagrams for LOAM and CLAY, respectively. It can be noticed that the WWL agrees well with those values established by the air permeability test.

(iii) <u>Dry Workability limit (Drop Test)</u>

Figure 42 shows the results of the test for LOAM. These are the MWDs obtained through applying specific energy at four soil water potentials (pF 5.4, 4.8, 4.3 and 3.1) ranging from dry soil to the lower part of friable state.

Power curve relationships were found also by Hadas and Wolf (1984) using a drop-shatter fragmentation method. When soil moisture content increases, more energy does not result in more reduction of the size of the aggregates produced. Since this test is focussed on the dry side, it is necessary to look at the moisture content at the point where the technological result of tillage is not attained.

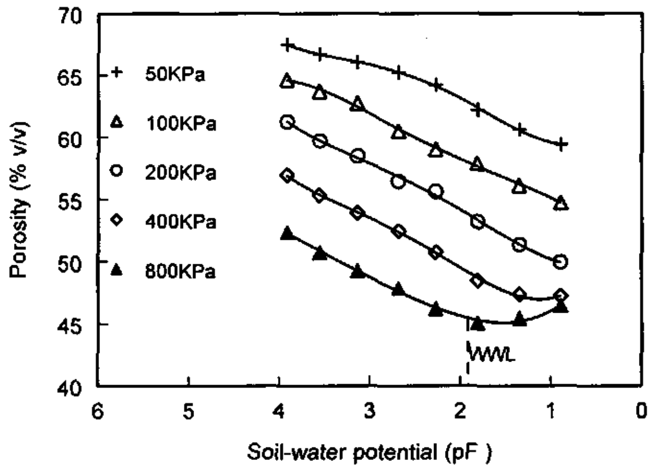


Fig. 40. *Wet Workability Limit as determined by the MPV diagram for the* LOAM *soil.*

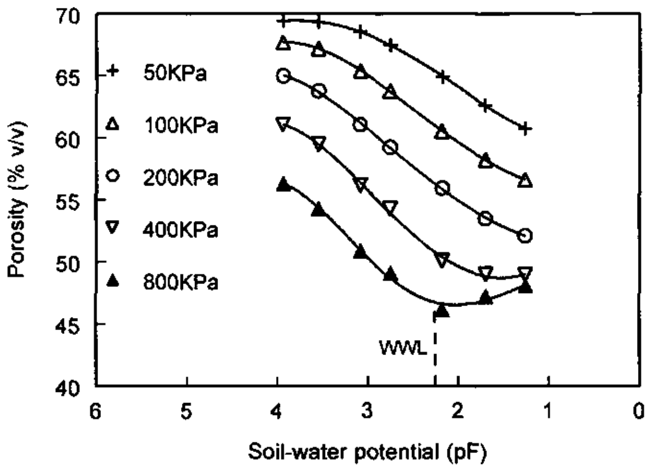


Fig. 41. *Wet Workability Limit as determined by the MPV diagram for the* CLAY *soil.*

As considered earlier, an MWD of around 15 mm would yield an adequate seedbed, and it can be seen that at pF 3.1 this MWD is produced with a low energy input of 55 J kg $^{-1}$. The soil water potential just is the same found in the field to be the dry boundary to obtain an adequate seedbed (Fig 23).

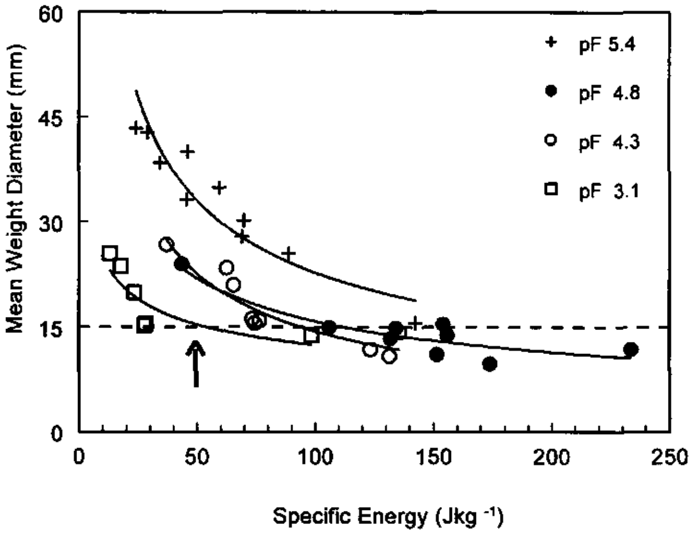


Fig. 42. *MWD obtained after applying specific energy at different soil-water potentials for* LOAM.

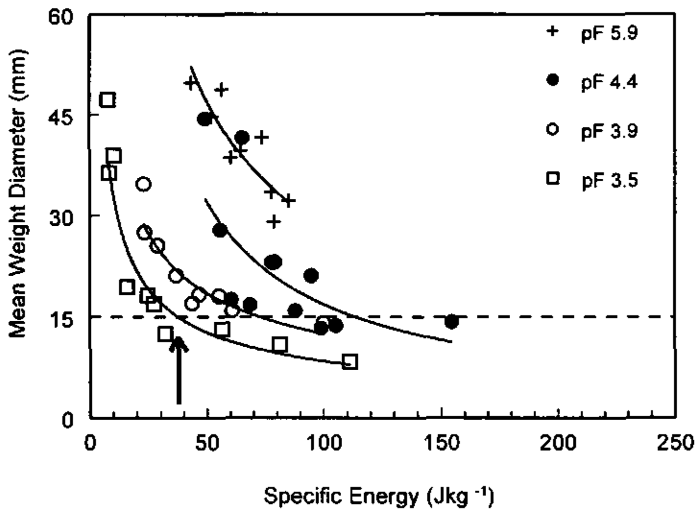


Fig. 43. *MWD obtained after applying specific energy at different soil-water potentials for* CLAY.

Figure 43 shows the results of the drop test for CLAY. It can be seen that moisture levels tested are around the shrinkage limit. A value of 38 J kg^{-1} at pF 3.5 is feasible due to crack formation inside natural test clods.

The best fit of the relationship between specific energy applied and the MWD obtained at different moisture contents is found by power curves.

As for LOAM, there is also a clear relationship between soil-water potential, the energy input and the MWD. According to the results, using 15 mm MWD as a criterion again, tillage should be done until the soil reaches a moisture content of around pF 3.5 as it is drying out. This value well agrees with the dry boundary found in the field (Figure 23) for obtaining an adequate seedbed for this soil.

In conclusion: At SL, the required MWD can be produced with acceptable energy consumption. In the drier range specific energy increases strongly, and in very dry soil the MWD cannot be obtained (clods remain too coarse).

The range of moisture content at which adequate seedbed is produced in the field, can be well represented by the laboratory tests. This is very important because the workability limits for the clay and loam soils of the area under study can be established following those procedures.

3.2.4 Links and discrepancies between field workability criteria and its representation by laboratory tests

Thresholds for optimum and suboptimum technological results

From the field experiments, only the aggregate size distribution at planting depth had suboptimum results in relation to the soil matric potential for LOAM and CLAY. Other resultant effects such as bulk density, and surface relief, distribution of aggregates at surface had no suboptimum results.

In Table 8, the field thresholds, in terms of pF, where optimum and suboptimum results appeared are shown together with the thresholds found in the laboratory for 'wet' and 'dry' workability limits. Also in the table, the thresholds of the theoretical workable range based on the consistency limits (PL and SL) are shown for comparison. with those obtained in both the field and the laboratory.

The 'wet' workability limit from the field experiments agrees well with the one found in the laboratory based on the air permeability test and the MPV diagram. Those thresholds are also in agreement with the theoretical 'wet' threshold represented by the plastic limit (PL) for both soils.

For the 'dry' workability limit, in LOAM, an adequate result of aggregates up to 15 mm MWD was achieved in the field until a dry boundary of pF 3.1 (Figure 23). In the laboratory working at pF 3.1 the lowest specific energy to obtain 15 mm MWD was 55 J kg^{-1}

For CLAY, in the field, 15 mm MWD was obtained up to a dry boundary of pF 3.4 (Figure 23). In the laboratory 38 J kg^{-1} where needed to reduce the aggregates to these size working at pF 3.5.

For the 'wet' part of the soil, the limits found in the field and the laboratory agreed rather well with the 'theoretical' plastic limit (PL), whereas for the 'dry' part of the soil, the limits found in the field and the laboratory are in discrepancy with the 'theoretical' dry shrinkage limit (SL) for both soils.

Table 8. *Thresholds (soil-water potential) as workability limits for LOAM and CLAY from field and laboratory experiments. The theoretical limits (PL and SL) are also shown.*

Experiment	LOAM (pF)	CLAY (pF)
'Wet' workability limit		
MWD of aggregates at planting depth (in field)	1.9	2.1
Air permeability test (in laboratory)	2.0	2.1
M-P-V Diagram (in laboratory)	1.8	2.2
Plastic Limit (from laboratory)	1.9	2.2
'Dry' workability limit		
MWD of aggregates at planting depth (in field)	3.1	3.4
Drop test (in laboratory)	3.1	3.5
Shrinkage limit (from laboratory)	3.6	4.1

Moisture content for applying the least energy to obtain the desired result.

It was concluded already in chapter 3.2.2.2 that when using the tractor, the lowest energy applied in the field for obtaining an adequate seedbed was performing a shallow ploughing and then harrowing at pF 3.3 for CLAY, at pF 3.1 for LOAM, and at pF 2.5 for SAND. This agrees well with the laboratory experiments where the lowest amount of energy applied to the soil to obtain a MWD of 15 mm, coming from very dry condition, looking for some moisture content above the SL, the aimed result was attained at pF 3.5 and 3.1 for CLAY and LOAM, respectively.

3.2.5 Possibilities for developing workability criteria to support decisions on tillage

Field and laboratory results agree well. Thus the laboratory methods described earlier can be used in order to establish the moisture values within good technological results can be attained. This will enable to produce the workability data needed in a procedure of analysis of information to draw conclusions that will support the planning and operational decisions on tillage, based in soil workability criteria.

4 PREDICTION OF MOISTURE STATUS IN THE SOIL FOR TILLAGE PURPOSES

4.1 Soil moisture information for tillage

4.1.1 Importance

The effect of a tillage tool on a given soil depends largely on the moisture content at which the operation is carried out (Spoor, 1977). Thus, it is very important to measure, calculate and predict the moisture status in the soil. Along with threshold values that delimit optimum soil water content at which a given implement attains a desired tillage result, this information enables the workable periods to be calculated.

The measurement (monitoring) of soil moisture content will provide quantitative information at *operational level* to support on-site decisions on the timing of tillage operations.

The calculation/prediction of soil moisture, and thus workable periods, will be the key tool at the *planning level* for calculation of the size and number of implements and power sources required by an established tillage system in order to meet timeliness objectives. It can also be used in another way: to find a suitable tillage system to work the agricultural land in the available time.

The monitoring of soil moisture for *operational purposes* is covered only briefly; the calculation/prediction of moisture status for *planning purposes* is more closely examined, because the *design or selection* of the tillage system(s) based on soil workability is the first important step towards timeliness of crop establishment.

4.1.2 Monitoring moisture status in the soil for tillage operational purposes

In principle, a quantitative site-specific decision can be made at operational level as to whether tillage will be carried out. For this an analysis of the soil moisture status in the profile should be done, comparing it with threshold values of the optimum range of moisture for tillage operations. The moisture status can be estimated using a gravimetric method (quick drying coupled with weighing), tensiometers, and gypsum blocks. The main objective is to establish a system that gives information in real time, or within a maximum of half an hour, because decisions need to be made relatively quickly. Other methods of moisture monitoring in the field are time domain reflectometry (TDR) and frequency domain (FD), which are based on the dielectric properties of the soil. These measurements can be done using a portable hand probe (Topp et al., 1984; Dalton and Van Genuchten, 1986; Perdok et al., 1996) and such electronic devices can also be readily multiplexed and data-logged for continuous monitoring of soil water (Dexter, 1997). However, these methods require calibrations, and the instruments are relatively expensive and not yet widely available.

Measurements of water content for on-site operational decisions are very important in production systems using mechanical traction, in order to avoid soil deterioration and/or waste of energy when the soil moisture status is in sub optimum condition for tillage. This approach is consistent with the concepts of farming by soil (Larson and Robert, 1991) and precision agriculture (Fulton et al., 1996, Bouma, 1997a). Working units (fields within the farm) must be delimited, by homogeneous texture and landscape position, at least in relation to tillage. This is done in order to reduce moisture status variability within each unit. For production systems with low energy input into traction, such as those using draught animals, operational decisions are self-regulated by the very limited availability of energy. Thus, tillage is carried out in a narrow range of moisture content, which will usually fall within the optimum range of conditions.

4.1.3 Water balance to calculate/predict workable periods for tillage planning purposes

Modelling the water balance

Many approaches were developed specifically for estimating workable periods based on the prediction of moisture content in the soil. Most models that have been used for predicting the soil moisture status in relation to tillage are based simply on soil moisture budgeting (Elliot et al., 1977; Witney et al., 1982; Simalenga and Have, 1992; Uresti and Campos, 1994). These models assume average soil characteristics according to soil type, and the full arable layer of soil (i.e. 30 cm) is considered. In this way, the average number of workable days (within a year, season, month, week) has been estimated at regional level.

An empirical model, known as the Versatile Soil Moisture Budget, was developed by Baier and Robertson (1966) and applied later by Baier (1973). This model estimates daily soil moisture from daily meteorological input data (precipitation and potential evapotranspiration), and drainage. The soil profile is divided into several layers with variable thickness, proportionally to their moisture holding capacity, as dependent on soil type.

Akinremi et al. (1997) tested a modified version of the Versatile Soil Moisture Budget in several sites of Canada during a period of eight years. It was a simulation at regional scale. The model was found to show good agreement between measured and predicted values, even at a regional scale. Nevertheless, discrepancies appeared due to spatial discretization of the studied region, and use of averaged values of input parameters.

A prediction model based on the soil moisture balance equation was used in Scotland (Witney, 1982, Witney *et al.*, 1982; Eradat Oskoui, 1988):

$m_h = m_p + P - R - D - E$ where m_h is soil moisture content of the soil layer down to depth h, m_p is soil moisture content on previous day, P is daily precipitation, R is surface runoff, D is drainage and E is evapotranspiration all in mm. This equation incorporates two main advantages: the model is cumulative and error compensating whenever the soil reaches saturation, and drainage is related to the hydraulic conductivity of the soil between saturation and field capacity. As the main difference from the Versatile Soil Moisture Budget, this latter model estimates drainage, not from the over-simplified concept of constant flow, but on the unsaturated soil dynamics (Darcy´s equation). The model uses hydraulic parameters (conductivity, moisture content at saturation and at field capacity) together with other soil and climatic data as inputs. The model, applied to Scottish soils, showed good correlation with actual values of soil moisture content measured over four years. Small differences where found, explained by local weather variation.

Earl (1997) used the mechanical status of the soil (penetration resistance using standardized cone at three depths) as a prediction of workability, and measured this simultaneously with the soil moisture status for six European soils throughout the year. Variation patterns for both variables were found to be similar and a relationship was estimated by means of regression. Strong correlations were found, especially for the top 50 mm.

For tillage, however, it is important to know not only the average water content in the profile to be worked, but also its distribution. This is especially true from one season to the other because, on the one hand, the bottom part of the worked layer could be at the right moisture content, but meanwhile the surface could be too wet causing excessive slippage and smearing by the tyres. On the other hand the soil surface could be of the right status for adequate traction, while the bottom of the worked layer could still be quite wet, so that smearing by implements and subsoil compaction by the wheel load is taking place.

Deterministic models have been developed to simulate water movement within and through soils. Those models provide an opportunity to develop improved information on water status in the soil (De Jong and Bootsma, 1997). These models normally use a relationship between matric potential and hydraulic conductivity to simulate infiltration, soil water redistribution throughout the soil profile, and percolation below the root zone (Connolly, 1998). For the reasons stated above (information on vertical moisture distribution), it would be much better to approach the water balance with a deterministic model rather than with a simple budgeting model. Various deterministic models are found. SWAP (van Dam et al., 1997) is a water management, crop production and solute transport model. GLOBAL (Novak and Majercak, 1992) is a model for soil water movement and crop production. LEACHMN (Wagenet and Hutson, 1989) has a mode that simulates soil water and solute movement. Finally, DAISY (Hansen et al., 1991) is used for modelling soil water and nitrogen dynamics in the soil -crop system.

Soil properties required

The prediction of soil water status in compartments within the same horizons of soil on a daily basis by a deterministic model, requires detailed knowledge of soil physical properties such as moisture retention characteristics, unsaturated hydraulic conductivity, etc. for each layer (Earl, 1997). In addition, information on processes playing around the soil surface (crusting or sealing, surface water detention) and at the bottom of the soil profile (deep drainage) is needed. The practical use of such models is therefore generally limited by lack of data on hydraulic properties of a particular soil.

The use of pedotransfer functions

Since tillage is performed in the top soil profile (i.e. 0-30 cm), it is very convenient to predict the distribution of moisture in compartments. As mentioned above, accurate approaches by rather complex simulation models for the movement of water in soil require detailed data. Soil hydraulic characteristics, such as water retention and hydraulic conductivity, are key inputs in these models. Soil physical properties have a spatial variation, and a large number of measurements must be done in order to characterize any agricultural land. The measurement of soil hydraulic characteristics is time consuming and costly. In the area under study there is a lack of this type of data, as most soils in the tropical area of Mexico are described only in terms of their texture (INEGI, 1987).

Pedotransfer functions (PTF) are an approach in which the hydraulic characteristics of soil are predicted from more easily measured or available data such as texture, organic matter content and bulk density, which are surveyed routinely (Bouma and Van Lanen, 1987; Wösten et al., 1995; Tomasella and Hodnett, 1998).

Most PTF's have been derived and validated using data sets from soils of the temperate regions, where chemical, physical and biological processes are different from those in the soils of the humid tropics (Tomassella and Hodnett, 1998). Thus caution should be exercised in applying PTF's to other soil and climatic conditions (Espino et al., 1995; Kay et al., 1997). However, pedotransfer functions are only as good as the original measured data from which they are derived (Stolte et al., 1996). This is particularly true in the tropical areas, where often not enough data are available to create a reliable pedotransfer function, since detailed information was collected in few and scattered locations.

Because of the fact that direct measurements of hydraulic characteristics will not be technically and financially possible in the near future for vast areas of the tropical area of Mexico, it is worthwhile to assess the reliability of PTF derived from other regions. However, it ought to be taken into account at least whether the soil under study falls within the range of soil textures that were originally used to derive the PTF's.

4.2 Assessing the use of PTF's for workability prediction

4.2.1 Moisture retention curves

Soil moisture retention characteristics were predicted for three soils from the tropical area of Mexico applying the following PTF's:

a) Pedotransfer functions developed from soil data from the United States of America (Rawls et al., 1982),

b) Continuous pedotransfer functions (Hercules computer programme) derived from the Staring soil data series in The Netherlands (Wösten et al., 1995; Stolte et al., 1996; Wösten, 1997),

c) Pedotransfer functions derived from soil data from the Amazonia region in Brazil (Tomasella and Hodnett, 1998), and

d) Continuous pedotransfer functions derived from the Hypres data base of European soils (Wösten et al., 1998).

A comparison of soil data measured in the laboratory against predicted data using PTF's is shown in Figures 44 to 47. The comparison was made for the three soils (LOAM, CLAY and SAND) described earlier in Table 3, in the range from around pF 1.5 to around pF 4.5, which is the moisture range of interest in this tillage study. It can be observed in Figure 44 that PTF's from Rawls et al. (1982), did not allow a good estimation of the moisture retention for all soils. These PTF's are among the earliest developed, and they predict the volumetric water content (θ) for specific points of interest of suction (h), so a specific PTF has been developed for each point of interest. Tietje and Tapkenhinrichs (1993) have evaluated the accuracy of different PTF's applied to a wide range of German soils. Among others, they tested the PTF's from Rawls et al. (1982). They conclude that these PTF's are not applicable for modelling purposes because (i) the low water potential range is missing and (ii) the slope of the retention curve has a systematic error, and overprediction of water contents occurs at low suctions and underestimation at high suctions. This trend was also found for the soils studied, as shown in Figure 44.

Tomasella and Hodnett, (1998) found an overprediction of θ at an h of 33 kPa (around pF 2.5) when using the PTF from Rawls et al. (1982) for soils from

Brazilian Amazonia.

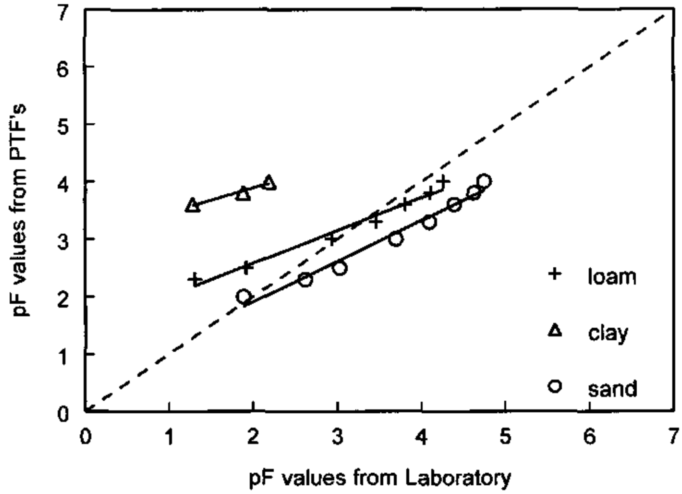


Fig. 44. *Relationship between measured and predicted pF values; PTF's from Rawls et al. (1982).*

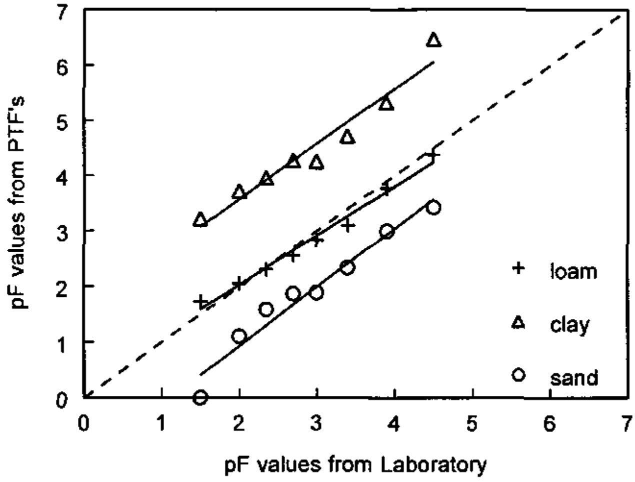


Fig. 45. *Relationship between measured and predicted pF values; PTF's from The Staring Series (Stolte et al., 1996).*

In Figure 45, the application of the Hercules program (PTF's from the Staring soil series in The Netherlands, Stolte et al., 1996), resulted in a rather good estimation of the retention curve for LOAM. The predicted and measured suction values for this soil showed a close fit. For CLAY, the predicted suction values are higher than those measured in the laboratory, and for SAND predicted suction values are lower. However, it can be observed as well that the curves for the latter two soils, are quite parallel to the ideal 1:1 line. Overprediction of suction for CLAY is 1.5, and under prediction for the suction of SAND is 1 (in pF units).

Regarding the PTF's from Tomasella and Hodnett, (1998), it can be seen from Figure 46 that there is a tendency to overpredict moisture at low matric potentials and to underpredict at high matric potentials. This PTF was developed to predict Brooks-Corey parameters (Brooks and Corey, 1964) of the water retention curve.

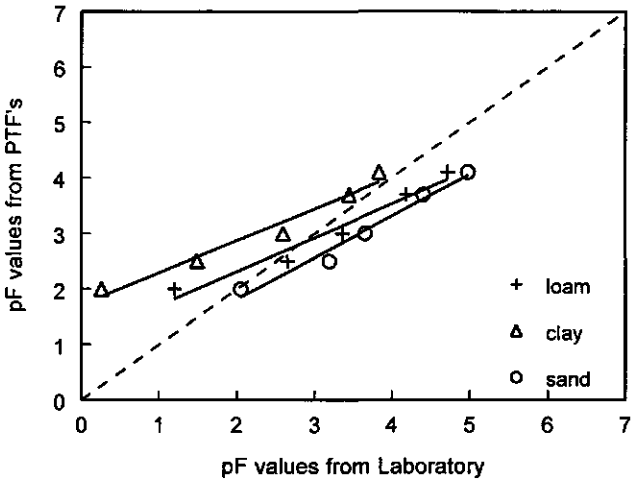


Fig. 46. *Relationship between measured and predicted pF values; PTF's from Tomassella and Hodnett, (1998).*

Figure 47 shows the comparison of pF values for the PTF derived from the Hypres database, which comprises a broad range of European soils (Wösten et al., 1998) with measured data. The relationship for LOAM is almost in the 1:1 line, while for CLAY suctions are highly overpredicted and there is a tendency that overprediction increases as moisture content in the soil decreases. The suctions for the coarse textured soil are underpredicted and there was a tendency to increased underprediction of the suction at higher values.

Possible explanations of the differences between predicted and measured data of the moisture retention curve are :

The hydraulic data from which PTF's from Rawls et al. (1982) were derived covered just a suction range of pF 2 to pF 3.3 and probably many data sets had few points of the retention curve. The authors mention that the Brooks and Corey equation was fitted to all water retention data that had five or more observations. They also mention that diverse methods were used to obtain the data. It is not clear if this applied to different ranges of the curve, or even to points within a range. The PTF's can be applied to any soil, as they were not developed specifically for loam, sandy or clay soils. The authors mention that when predicting the values of water (v/v) retained at 1/3 bar for clay and sandy clay textures, these are greater than the effective porosity for these soils which is not physically possible, and they believe that it was a result of averaging.

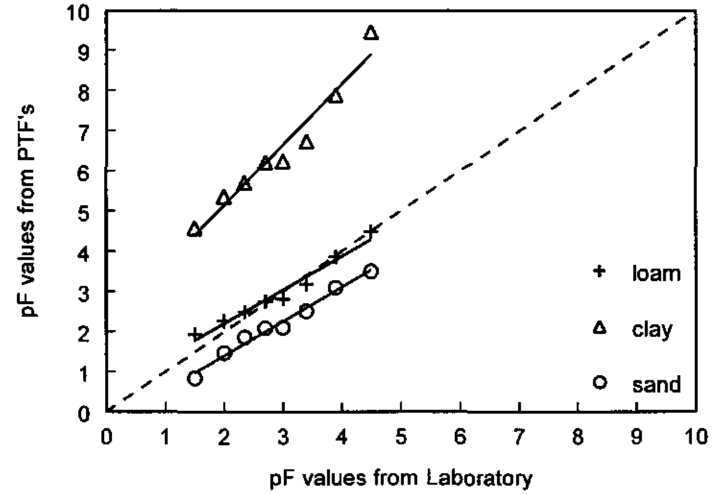


Fig. 47. *Relationship between measured and predicted pF values; PTF's from the HYPRES database. Wösten et al. (1998)*

Better results were predicted with the Dutch PTF's, probably because the data sets (moisture retention curves and hydraulic conductivity curves) from which these were derived are rather unique in the following ways: 1) they covered a broad spectrum of soil types, 2) the same methods were used on a routine basis to measure specific ranges of the curves and measurements were made to undisturbed samples in the laboratory, and 3) distinctive continuous PTF's were also derived, one for coarse textured soil and another for medium and fine textured soils. A distinction was also made between topsoil and subsoil. The Dutch PTF's are regarded as model parameter prediction methods for the prediction of the water retention function (Wösten, 1997). To derive these PTF's, all individually measured hydraulic characteristics were parameterized using the non linear least-squares optimization program RETC (Van Genuchten et al., 1991). Parameterization methods are used to predict parameters in a model describing the θ-h-K relationship. This approach has the advantage of being more efficient than the point prediction PTF's for their use in simulation models.
With regard to the PTF's from Tomasella and Hodnett (1998), these authors mention that of the data sets used to derive the PTF's, few had detailed soil water retention data available, but others were limited to information on porosity and/or water contents at matric potentials of - 33 kPa and -1500 kPa. This may be the reason why prediction of the retention curve for the soils assessed here was not

good, even if better prediction was expected since those are soils from the tropical area of Mexico.
The PTF's derived from the Hypres database were developed using the same procedure as those from the Staring series. In fact this series is part of the Hypres database. Different results were obtained because data from many other soils were used. The correlation coefficients for the regressions predicting the parameters and transformed model parameters that will describe the retention curves are lower than those derived from the Dutch soils alone. Also, the Hypres PTF's are for all types of soils, and in this case no distinction was made between coarse medium and fine textured soils.

4.2.2 Hydraulic conductivity curves

The hydraulic conductivity curve is the other characteristic of the soil needed as input in a deterministic model for water balance. Measurements of saturated hydraulic conductivity (K_{sat}) have been made in laboratory (using the constant head method) and compared against predicted values only for the medium and fine textured soils. The values of unsaturated hydraulic conductivity (K_{unsat}) for LOAM and CLAY were obtained using the RETC code (van Genuchten et al., 1991) using as input the measured values of the moisture retention curve and the measured values of K_{sat}.
Only the Dutch and European PTF's predict the transformed model parameters that describe the hydraulic conductivity curve using quantities of texture composition and organic matter of a specific soil. Rawls et al. (1982) give one equation to predict only the K_{sat} for a given soil textural group. In Tomasella and Hodnett (1998), no PTF's were developed for predicting the hydraulic conductivity curve.
Values of hydraulic conductivity (K_{sat} and K_{unsat}) were only predicted using the Dutch PTF's. The values of measured saturated hydraulic conductivities in the laboratory and those predicted by the PTF's have differences within an order of magnitude for LOAM (6.8 cm d^{-1} and 93.1 cm d^{-1}) and rather, no difference for CLAY (106.3 cm d^{-1} and 97.6 cm d^{-1}). In the literature it can be found that the differences for LOAM are within a normal range. Hillel (1971) states that in a saturated soil of stable structure, as well as in a rigid porous medium such as sandstone, the hydraulic conductivity is characteristically constant. Its order of magnitude is about 10^{-2} to 10^{-3} cm s^{-1} (864 to 86.4 cm d^{-1}) in sandy soil and 10^{-4} to 10^{-7} cm s^{-1} (8.64 to 8.64×10^{-3} cm d^{-1}) for a clayey soil. Within the same soil type, the hydraulic conductivity varies if the soil is highly porous, fractured or aggregated, or compacted and dense. In the field, apart from tillage effects, cracks, worm holes and decayed root channels will affect the movement of water, so the pore

geometry of the soil is the main property which affects the hydraulic conductivity.

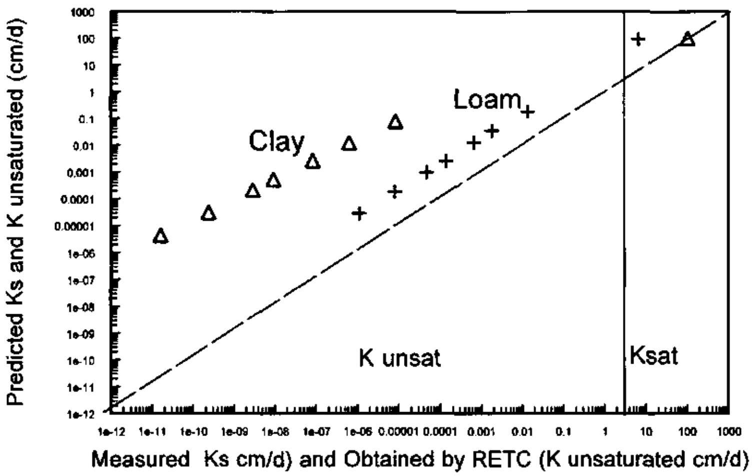


Fig. 48. *Relationship between values of measured Ksat in the laboratory, estimated K_{unsat} by RETC code, with the predicted values of K_{sat} and K_{unsat} using the PTF's from the Staring series. (Stolte et al., 1996).*

The hydraulic conductivity near saturation is determined primarily by soil structure properties which are known to be subject to considerable spatial variability in the field. This is in contrast to soil textural properties, which generally are less variable and have a more dominant effect on K in the dry range (van Genuchten et al., 1991). Wösten (1997) showed that with individually measured values of K_{sat} for a top soil horizon with a silt-loam texture, having between 85% and 100% clay and silt, the K_{sat} varies in more than two orders of magnitude. K_{sat} is one of the transformed parameters to describe the hydraulic conductivity curve. It is observed that from all Dutch continuous PTF's (Wösten, 1997) the PTF for predicting this parameter has the lowest correlation coefficient (R^2 =32% for coarse soils and R^2 =30% for medium and fine soils).

In Figure 48, the values obtained by using the RETC code and predicted values of K_{unsat} within a range of pF 1.5 to 4 are compared, as well as the measured and predicted K_{sat}. In the dry range, it is thought that the curve can be rather well predicted by the Dutch PTF's for LOAM. The line that makes up the values obtained through the RETC code and predicted values from the PTF's for this soil is parallel to an ideal 1:1. The differences in between the values are within one order of magnitude, and the predicted K_{sat} is also one order of magnitude greater than that measured in the laboratory. In the same Figure 48, it can be seen that for CLAY the line is also quite parallel, but the distance is about 4 orders of magnitude with respect to the ideal line for K_{unsat}, while the K_{sat} is accurately predicted.

5 SOIL WORKABILITY INFORMATION: spatial characteristics

5.1 Introduction

The computation of workable periods is based on two components: 1) data on soil-weather interaction (soil water balance) and 2) the threshold values (workability limits) that delimit the optimum state of soil for aimed results from tillage. Information on workable periods can be used as a planning tool to allocate suitable tillage systems, and if possible, at different spatial scales. It could also be used to assist operational decisions on tillage at farm/field level. The quality and quantity of data available to calculate the water balance and the availability of a method or technique to establish quantitative or qualitative workability limits will dictate how the information on workable periods shall be used. In this chapter, the effect of spatial scale on the water balance is reviewed. After this, the possibilities of applying the methodology presented in Chapters 3 and 4 with limited data available are discussed.

5.1.1 Soil water balance and spatial scales

As mentioned in Chapter 4.1.2, for tillage purposes the soil moisture regime is predicted on a regional scale and over periods of months and years (Rounsevell and Jones, 1993). Simple moisture budgeting has frequently been the tool applied to estimate the soil moisture regime. The lack of accuracy of these models in relation to the information relevant for soil workability has also been mentioned. Few authors have used deterministic models (Van Wijk and Buitendijk, 1988), which give much better relevant information but require more detailed data (hydraulic characteristics of the soil) to predict the moisture regime of a specific site.

Hydraulic characteristics such as the moisture retention and conductivity curves have inherent spatial variability, and it is not feasible to measure the huge amount of data required to characterize even the field level scale (Van Dam et al., 1998). Approaches to quantify upscaling of the water flow process are being studied, from where it is spatially well understood and mathematically described (scale of 10^{-1}m) to scales such as field (scale 10^2 m) or catchment (scale 10^3m) where they need to be represented (Feddes et al., 1993; Kim, 1995; Kabat et al., 1997). One of the most promising techniques used to scale and aggregate the soil characteristics is the use of reference curves for water retention and hydraulic conductivity obtained through "similar media scaling" (Kim, 1995). Further studies are needed to confirm that a relatively simple method (reference curve) will become available to parameterize soil variability at large scales (Kabat et al.,

1997). In the SWAP model (Van Dam et al., 1997) this similar media scaling method is used to deal with the spatial variability of the soil hydraulic functions when calculating the moisture balance at field level. The authors have calculated the water balance with the model in a catchment of 160 ha (corresponding to a scale 10^3 m).
According to Kabat et al. (1997) it is still difficult to accurately model the soil water balance for large areas, although techniques to parameterize and scale up heterogeneous soil hydrological processes exist; the scaling and aggregation of soil hydraulic characteristics for such mixed soil types (as it will be usually found at any agricultural area) remains largely unexplored. Deterministic models use specific site data to calculate the water balance, thus care must be taken in attempting to use these to model the water balance of large areas. Modelling systems that can function at a number of different scales are increasingly needed, and various authors advice caution regarding possible pitfalls and misuse of information in this context. According to Smith (1996), a change in scale implies a change in the resolution of input and output values. Whether to scale up or down depends on the proper identification of different processes that are specific to each scale (Fresco, 1995). Upscaling reduces accuracy and increases heterogeneity (Smith, 1996). Pitfalls are associated with using point data in models to represent the behaviour of large areas of land (Bouma, 1997b). There should be an optimum scale of operation at which each process can and must be studied (Fresco, 1995).
Specifically for tillage planning in tropical areas, there is a need for techniques that measure soil hydrological and water balance variables at large spatial scales. This is because soil data required for modelling is actually not usually available. Because very limited information is available, very simple budgeting is used up to now to model the soil moisture regime for tillage purposes in the tropics of Mexico (Uresti and Campos, 1994; De Jong, 1997). It is more realistic that soil hydraulic characteristics will be measured only in relatively few locations for most agricultural areas of the tropics of Mexico.
One alternative possibility for obtaining hydraulic characteristics of soils for large areas is the use of pedotransfer functions. Using this technique, relevant information is derived from data on soil texture and organic matter, as discussed in Chapter 4.1.3. For the LOAM soil of the area under study, PTF's from the Staring series (Wösten, 1997) can predict the hydraulic characteristics well. This is a good start, since most of the soils under agricultural use in the area under study are medium textured. For the fine textured soils, it is also worthwhile to carry out further tests to verify whether a correction factor may be used to predict data from the same Dutch PTF's. However, if after further tests these PTF's cannot be used for the CLAY soils it is necessary to develop local PTF's. In this case a further

question appears as to how to generate the data to build reliable PTF's. There is the need for the direct determination, in the field or in the laboratory, of hydraulic properties from a minimum number of locations. It is also worthwhile to explore the possibility of the validation and use of integral methods (Shao and Horton, 1998). With this approach, horizontal infiltration experiments are conducted in laboratory in order to estimate the Mualem (1976) and van Genuchten parameters and thus the soil hydraulic characteristics. This can be accomplished in a few days.

In seeking options to generate the required data, the above mentioned method seems a good option for generating information that could be used as direct input for modelling the water balance at field and farm scale.

5.1.2 Workability limits and spatial scales

Thresholds as soil moisture limits that are critical for workability have been studied mainly in the humid temperate countries. Thus it was important to set a limit in wet soil to avoid damage of soil structure by compaction. In studies at regional scale, percentage of the field capacity (Witney and Eradat Oskui, 1982) and a critical moisture deficit for a given depth of soil (Rounsevell and Jones, 1983; Earl, 1997) have been used as thresholds for workable condition of soil.

Workability limits applied at field scale for the wet part of the soil can be established by laboratory methods (Perdok and Hendrikse,1982; Lerink, 1994). Water tension values of the topsoil (Van Wijk and Buitendijk, 1988) have also been used at field level as thresholds for workable condition in wet soil.

In the tropical area of Mexico, it is important to set thresholds at wet and dry soil. At a regional scale in the area under study, the empirical plastic and shrinkage limits are used to establish the workable range of the soils (Uresti and Campos, 1994).

5.2 Workability and scaling

In this work, field studies have been carried out to set thresholds where tillage results change from optimum to sub-optimum for soils in the tropical area of Mexico. Laboratory experiments were performed and results from quite simple tests were found to represent the limits from the field well (as presented in Chapter 3.2). Through the use of a deterministic model, the water balance can be calculated for the soils under study using measured hydraulic characteristics and local climatic data. In principle this methodology allows to quantify the workable periods for a specific site, where all the field data were measured directly. However in the area under study, a full data set for direct application of this methodology will not always be available. Figure 49 shows that, as the area to be represented increases in size, the availability and degree of detail of soil and weather data decreases.

The possibility of extending the methodology developed at experimental field scale for use at larger scales using the available information in the spatial scales identified in the region, will be discussed in the following paragraphs. Workable periods for the site where Cotaxtla farm is located, will be calculated at the different scales. To illustrate the scales, the location of the farm is given as a reference in the available maps.

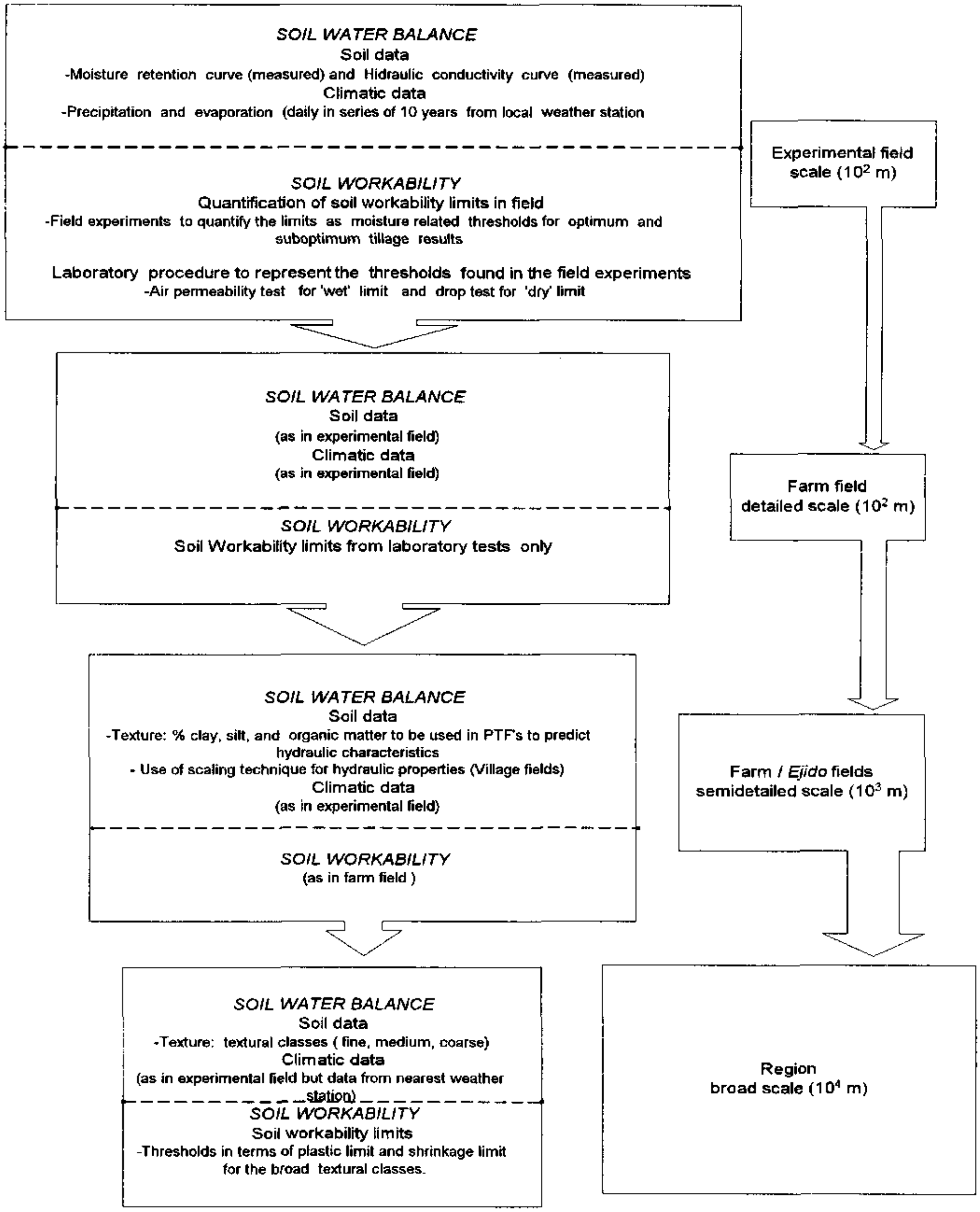


Fig. 49. *Availability of information for the soil water balance and workability limits for the spatial scales identified in the area under study.*

5.2.1 Field scale

5.2.1.1 Description

For the tropical area of Mexico and in relation to tillage activities, this scale refers to a field within a farm. According to the soil texture variability and the size of farms in the region, each field could range from around 5 to 25 ha in size. In order to reduce the spatial variation of soil type, the field is delimited by soil characteristics such as texture and organic matter in a layer of the soil profile (i.e. 0 - 15 cm depth) and position in the landscape. It is very important to delimit the soil, in order to identify a relatively homogenous piece of land when assessing moisture content for workability.

A map of the farm is produced including the location of the soil units and its area. Variation in soil type within a delimited unit can be found with depth, which must be taken into account when modelling the water status and for application of the thresholds of workable range. For example Figure 50 shows part of the plan of the farm of Cotaxtla Research Station with the delimitations of the LOAM and the CLAY soils. These soils are described in Table 3.

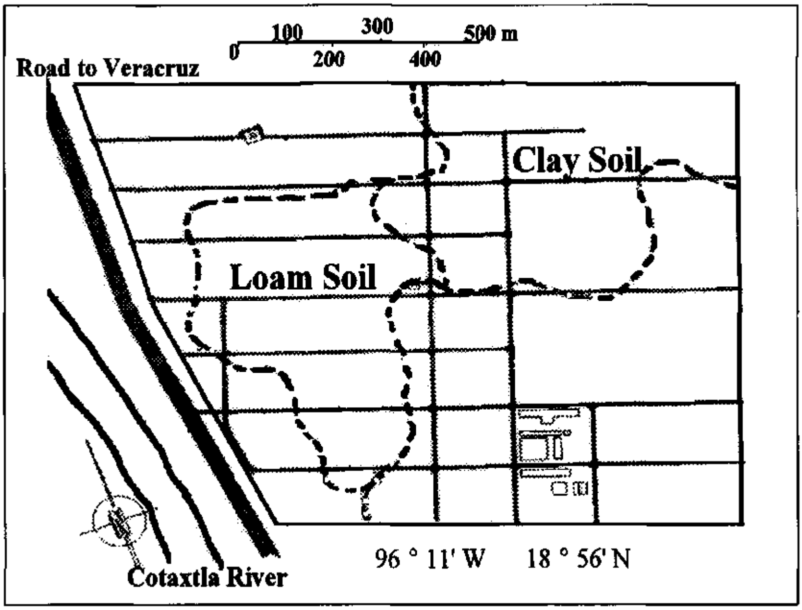


Fig. 50. *Detailed plan of the Cotaxtla farm showing the location of the* LOAM *and* CLAY *soils.*

At this scale, soil workability information is used at two levels, depending on whether the moisture status is predicted or measured:
First, at *planning* level the workability criteria is used together with the prediction of the soil moisture status for calculating the workable periods in a field (days per week, month, season or year). This will be the time to be matched by the tillage system.
At the second level in this scale, the workability information is used for *timing* the tillage operations. At this level, a scheme for monitoring the soil moisture status must be devised, and values compared with the trafficable/workable range in order to decide whether operations can be carried out.

5.2.1.2 Procedure for planning

A specific data set must be available for each field when using the workability information for planning where the following aspects are included:

Crop information
Seedbed quality required in terms of mean weight diameter (MWD) at planting depth, and the optimum range of planting dates (to complete the tillage activities for a timely crop establishment).

Soil physical information
Data on water retention characteristics and hydraulic conductivity. (Must be measured in the laboratory for each layer in the delimited field).

Soil workability limits
The workable range of the soil, to be determined by laboratory tests, as described in Chapter 3.1.4. For each soil unit, the following data must be determined:

Dry limit
As a first reference for setting a dry workability limit, the shrinkage limit (SL) of the soil is determined. After this, a drop test must be carried out in at least four moisture contents, two wetter than and two drier than the SL, each value separated by about 3% of moisture content (w/w). The results of the drop test (energy input, MWD and moisture content) must be compared with the seedbed quality required at planting depth in order to set the dry workability limit.

Air permeability
This test must also be carried out for each soil unit in order to determine the wet

workability limit.

Climatic Data

Climatic information through a database from e.g. a local climatic station must be available. Historical data (a series of at least ten years as is available in the area under study) on daily precipitation and evaporation are necessary for use as input in the modelling of the soil water. The weather data to be used should cover at least the period when tillage has to be performed in the cropping calendar.

Calculation/prediction of workable periods

By combining the soil physical and the meteorological data, a water balance can be calculated. The deterministic model SWATRE (Feddes et al., 1978; Belmans et al., 1983; Kabat et al., 1992) has been chosen to calculate the water balance. SWATRE is a transient, one-dimensional soil water flow model which uses soil physical properties, crop characteristics and weather data to estimate the soil water balance on a daily basis. This model was chosen because the output allows representation of the distribution of water in the profile in layers (with different hydraulic characteristics) and compartments within layers. As mentioned earlier, this representation is very convenient for a daily analysis of soil moisture status in relation to tillage. The water balance can be determined without the computation of crop growth, as is the situation for tillage in the area under study. The lower boundary condition set in the model for the water balance was free drainage at the bottom of an unsaturated profile. The upper boundary conditions were daily reference evapotranspiration and daily precipitation, plus a minimum allowed pressure head at the soil surface. In the area under study, conventional tillage is normally is carried out up to around 25 cm depth, and the working depth rarely reaches 30 cm. Because of this maximum working depth, it will be convenient to divide the profile (i.e. assuming one layer of equal hydraulic characteristics) as follows: at the top into thin compartments of about 1 cm up to the first 5 cm depth. This is done in order to look at the changes in water content in detail because changes can be very rapid in this zone in response to meteorological conditions. This is also very important to assess, if the soil surface is in a condition to be trafficable. Deeper, the soil can be divided into compartments 5 cm thick up to 30 cm depth, and 10 cm thick up to 40 through 50 cm depth.

Power sources and implements

The number and power capacity of tractors and/or the number of working animals must be quantified as well as the type and size of implements in the farm. The working capacity of a given power source-implement combination must be known.

Workability-based decisions for planning can be made as follows:

1) When a particular tillage system has been fixed upon for an area (i.e. on steep slopes only direct planting is recommended, due to the high risk of soil erosion), then the number and size of implements and power sources can be quantified to match the workable time.
2) When the availability of power is a limiting factor, size of implements and power sources and then the capacity of the suitable implement-power source combination can be quantified for different tillage options compared with the available time. In this way an alternative tillage system can be recommended.
3) Actual tillage practices can be reconsidered. From the analysis of the vertical distribution of moisture in the soil profile, optimum periods for different tillage options can be quantified. Thus direct drilling and shallow tillage could be a better alternative than conventional tillage for some soil units.
4) From the analysis of the distribution of moisture in the profile it could be predicted how often a specific situation may occur. This information will form the basis of the economic assessment for a particular field as to whether it would be better to employ an alternative soil-traffic-tillage system in some years (i.e. when the shortest workable period occurs in the cropping calendar), instead being limited to only one option (according to a typical workable period within the cropping calendar). Limiting a field to a single tillage option may sometimes lead to delay of crop establishment and/or poor technological results or even soil degradation due to being forced to work in suboptimum conditions in order to establish the crop on time. With an emergency system (i.e. direct planting or some variant of minimum tillage) designed for the shortest workable period it would be possible to establish the crop on time just by switching to this tillage system.

5.2.1.3 Workability information for operational purposes

The data needed for operational decisions are the workability limits and the current status of the moisture in the profile. The workable range of a field (soil unit) is defined by the laboratory test, as described in Chapter 3.3. The moisture status of the field should be measured or estimated in real time.

After the definition of the workability limits, the most important aspect of the operational mode is the assessment of the moisture status within the considered space (horizontal and vertical) in real time. some options are mentioned in Chapter 4.1.2.

Some aspects of the procedure farmers follow in making a decision in favour or against tillage include: (1) the amount of sinkage and smear experienced while walking on the land; (2) the ease with which a walking stick can be pushed into the soil (i.e. a measure of penetration resistance); (3) the tendency of soil to stick to boots (i.e. a measure of adhesion); (4) the mode of failure of clods squeezed by hand (i.e. plastic deformation or brittle failure); (5) visual appearance of the soil surface (i.e. wet or dry). Few farmers dig holes when assessing the soil moisture status; most assessment is concerned with soil surface conditions. Farmers in the area under study also follow some of those aspects mentioned. Currently operational decisions on tillage are made by the farmer following his judgement, rather than well established protocols.

The planning-design of tillage will make operational decisions easier. If tillage systems can be planned-designed (including options for extreme years) according to the soil-weather, crop and environmental factors, it will help the farmers in that they will not face dilemmas such as deciding in favour of tillage in suboptimum conditions because of the pressure to establish crops on time.

5.2.1.4 Example of the application of methodology at field scale

The information from the field with the LOAM soil at the farm of Cotaxtla Station (located in Figure 50) is used. Cotaxtla Research Station, field Cecot-1 (Loam soil).

Crop information

Crop to be established: Maize. Aggregate size required at planting depth: 15 mm MWD in the layer from 40 to 80 mm depth. Optimum range of planting dates: May 15 to July 15. Area to be planted: 20 ha.

Soil workability limits

Workable range of the LOAM soil: pF 1.9 (wet) to pF 3.1 (dry).

Water balance

Soil data: Measured water retention characteristics and hydraulic conductivity (measured on field samples).

Climatic data: Daily rainfall and evapotranspiration from May 14 to July 15. For the example, a year (1967) from a periods of ten years (1964-1973) with a late onset of the rainy season was chosen. Data is collected from the meteorological station *"El Capital"* 1 km north of the Cotaxtla Station Farm. This information has been used to calculate workable periods for the region under study by Uresti and Campos (1994) allowing a comparison with results from the analysis at the regional scale.

Power source and implements

A tractor of 53 kW (70 hp) at the flywheel, disc plough and disc harrow and conventional planter. The gross working capacity of the combination tractor and disc plough is 5.4 h ha^{-1}. For tractor and disc harrow, the gross working capacity is 1.4 h ha^{-1}. For planting, gross working capacity is 2 h ha^{-1}.

Processing the information and analysis

The water balance for the period July 2 to 23 is shown in Figures 51a and b. Before and after these dates, the soil was always too dry and too wet, respectively. For the analysis of the profiles in this example, the workability limits were converted from pF values to volumetric water content. It can be seen that for this particular year, 3 days (July 4,5 and 8) were in the workable condition from 0 to 5 cm (not deep enough for the conventional system), and only 4 days (July 15, 17, 18 and 19) have an optimum workable status at the full depth of 0 to 22 cm, which is suitable for the conventional tillage system.

This means that for a no-till system, the first period of three days could have been used for direct drilling!

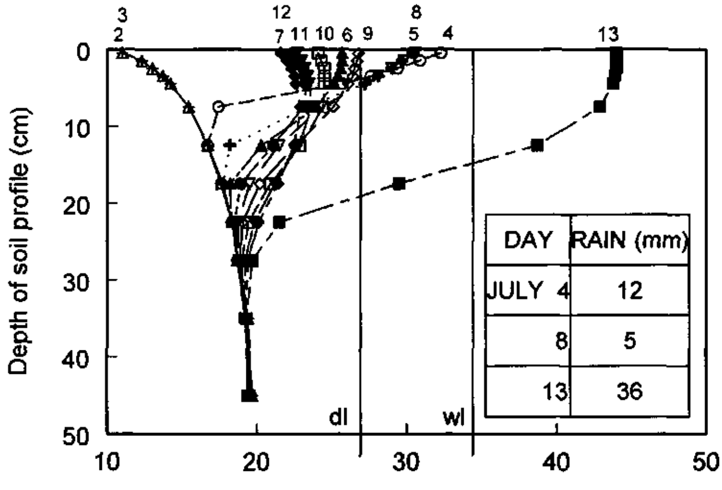


Fig. 51a. *Daily profiles of soil moisture content for a year with a late onset of rainfall season(1967). Period July 2nd to 13th.*

Based on the working capacity for the conventional tillage operations, in this case, 108 hours are needed to plough the 20 ha. Fifty-six hours for harrowing (two passes) and 40 hours for planting are required, assuming only one tractor and three implements are available. In this situation a lot of work is done in suboptimum conditions because little time is available in optimum conditions (even though very long working periods of as much as 16 h per day are found in the area under study) compared with that which is needed according to the working capacity. It was noticed in this case that the workable time appears at the very end of the optimum period for crop establishment. Because of this, it is likely that farmers will decide to perform all the tillage early in suboptimum soil moisture conditions, pressed to avoid delay in planting.

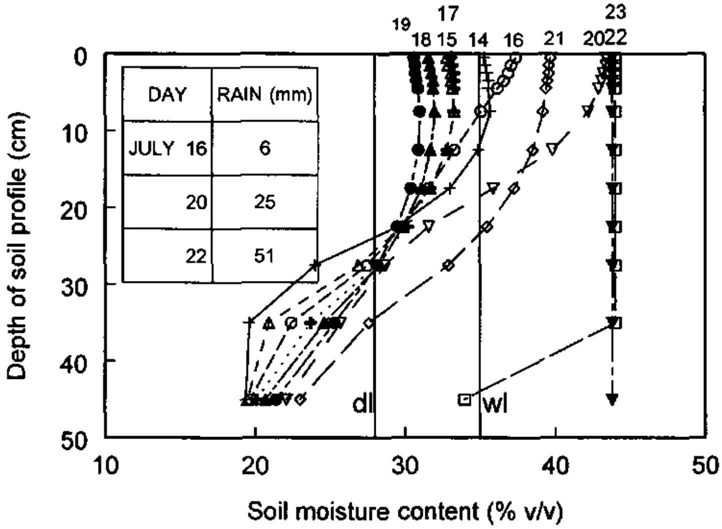


Fig. 51b. *Daily profiles of soil moisture content for a year with a late onset of rainfall season(1967). Period July 14th to 23rd.*

In Table 9 the workable periods for a period of 24 years (1964-1987) for the same LOAM soil are shown. It can be observed that in only two years (1972 and 1982) the conventional tillage could be done completely in optimum conditions for the 20 ha field since 204 hours (a minimum of 13 days if one counts very long working periods of 16 hours per day) were needed to complete the operations. For direct planting, the crop establishment could be done in optimum moisture condition for almost all the years (with exception of 1974 and 1983), since for the same area only 40 hours (2.5 days in working periods of 16 h) are needed with the same power source.

Figure 52 shows the probability of having a certain number of days with the soil moisture content within the workability limits for the LOAM soil at different depths in the profile. It is clear that for most of the years a tillage system working shallow (between 10 and 15 cm) will enable the operation (s) within the workability limits.

Table 9. *Workable periods for a series of 24 years for the LOAM soil within the optimum time (May 15th to July 15th) for maize establishment in Central Veracruz, Mexico.*

Year	'64	'65	'66	'67	'68	'69	'70	'71	'72	'73	'74	'75
	Number of days with soil moisture within the workability limits											
depth (cm)												
0 - 10	7	4	6	7	10	3	4	8	16	9	2	5
0 - 15	7	4	6	4	10	-	-	5	14	7	2	3
0 - 30	3	4	6	4	10	-	-	6	14	7	-	3
Year	'76	'77	'78	'79	'80	'81	'82	'83	'84	'85	'86	'87
	Number of days with soil moisture within the workability limits											
depth (cm)												
0 - 10	7	5	15	6	5	6	32	1	15	7	7	14
0 - 15	3	3	15	5	2	4	32	1	14	4	7	14
0 - 30	1	-	12	4	1	-	28	-	8	4	5	9

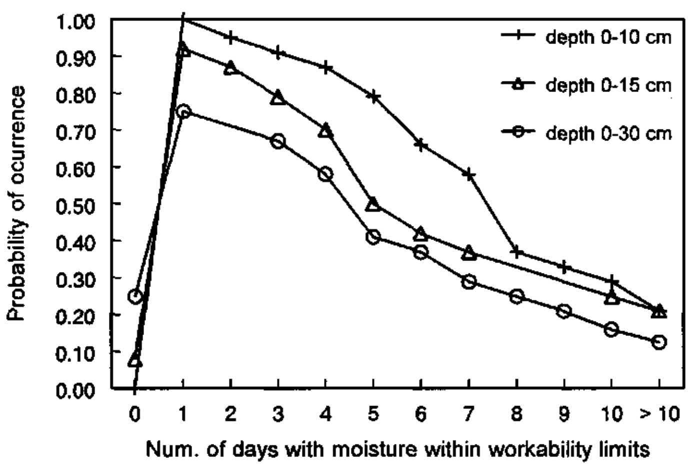


Fig. 52. *Probability of occurrence of days (period May 15th - July 15th) where the soil moisture will be within the workability limits at different depths. The calculation was made for a period of 24 years in Veracruz, Mexico.*

Not many alternatives in terms of tillage systems are available in the tropics of Mexico. Above results show that it will be important to investigate into development or selection of other tillage systems which allow a wider workability range.

5.2.2 Farm (semi-detailed) scale

5.2.2.1 Description

In the context of the tropical area of Mexico, this scale is referred to as the available information with respect to a specified farm. Typically the physical data on soils at this level is only available in terms of texture, organic matter content and sometimes bulk density. The information is available from records and reports from the surveys and experiments, and some come from commercial laboratories. The weather information comes from local or the nearest climatic station The semi-detailed information (on texture and organic matter) comes from fields (5 to 25 ha) that make up a farm or *Ejido* (organized community of farmers) which can consist of 100 to 500 ha of agricultural land. The location of the farms and meteorological stations can be exactly delimited in a topographical map of scale 1:50 000 (Figure 53). However, the field(s) from where the soil data were collected are neither located nor delimited.

The spatial soil unit is a specified farm. Thus the soil information (that was collected at one spot) represents the whole farm even if soil type may vary within the farm. This is indeed the case in the Cotaxtla farm (147 ha). However, it is also true that in other farms the soil texture does not vary, as is the case with the sandy soil in all the fields of nearby "Los Robles" (approximately 500 ha) located also in Figure 53. In this latter case the soil data collected at any spot represent well the whole farm.

When applying the methodology developed on experimental fields at farm level, measured data on soil hydraulic properties are missing. For use of a deterministic model for the soil water balance it is necessary to assume data or to derive the soil hydraulic characteristics using reliable PTF's. The workability limits can be determined through the laboratory test of samples from the spots of the farm from where textural information was collected.

The possibilities may be also explored to develop a type of PTF's to estimate the workability limits, based on texture and organic matter data such as reported by Terzaghi et al. (1988).

The calculation of workable periods is made for specified farms as those that are located in the topographical map of the area under study (Figure 53).

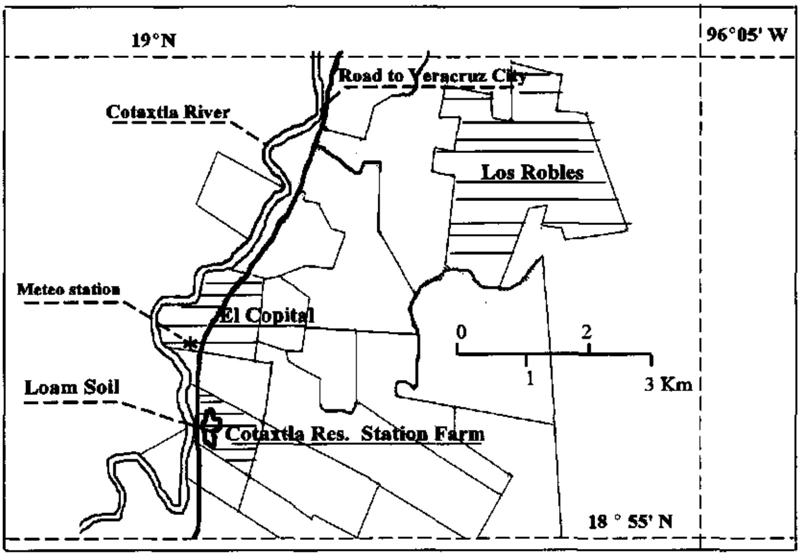


Fig. 53. *Location of the farm of Cotaxtla Station in a 1:50 000 topographical map of the area under study. The Cotaxtla farm where the* LOAM *soil is found (shown in detail in Figure 50) is also indicated. The fields of the farm "Los Robles" appear at the top right of the map.*

5.2.2.2 Data and procedure for using the workability information for planning

The data set required to model the water balance and to calculate the workable periods must be completed as in the field scale The basic difference is that the soil hydraulic properties are estimated by using PTF's, instead of being measured.

Crop information (see 5.2.1.2)

Soil physical information
Information on mechanical composition (% clay, % silt, % sand and % of organic matter). Pedotransfer functions (i.e. HERCULES (Stolte et al., 1996) for medium textured soils in the area of study) are used to predict the soil moisture retention and hydraulic conductivity characteristics. This dataset is calculated (estimated) for each place of origin of the input-data. For most farms, the information will come from one field which is not exactly located or delimited in area, so at the semi-detailed scale this information is taken as representative of the part of the

farm under cropping.

All other input and calculations (see 5.2.1.2)

5.2.2.3 Example of the application of the methodology at farm level

The same data of Cotaxtla farm as in the field level is used. So the workable periods calculated are the same as in the Field level. The difference is that in this case it is assumed that the soil information (thus the calculated workable periods) now is valid for the whole farm. In principle any area to be tilled is assumed to have the same soil characteristics. In the area under study, typically the data on soil texture will come from the part of the farm that is under cropping, and the farmer is the person who, from past experience, can delimit the location and size of the area that these data are representing.

Farm: Cotaxtla Farm: total area 147 ha

Crop information
As in 5.2.1.4, but the area to be worked within the farm is 25 ha where maize is planned to be established.

Soil workability limits
As in 5.2.1.4.

Water balance
As in 5.2.1.4, but here soil hydraulic characteristics are estimated by PTF's.

Power sources and implements
As in 5.2.1.4.

Analysis and considerations for the use of the information
In this example the part of the farm under cropping of maize (25 ha) is the spatial soil unit. It is assumed that the position of this unit is not exactly located within the farm and only the entire farm can be delimited and located in a topographical map scale 1:50 000 in the area under study (as shown in Fig 5.4). The problem at this scale is that the information derived on workable periods could have little meaning depending on the variability of the soils within a farm and or the size of the field from which the textural information comes (in this case it is known that the soil information is true for 20 ha since the textural information comes from the LOAM soil). It is assumed that the farmer utilises a rather uniform unit of soil and that by

past experience he has delimited the soil unit to make its textural and chemical analysis. At farm level, the delimitation of the area represented by the textural information lies in the judgement of the farmer. In this example it is intended to carry out tillage in 25 ha. Since it is known that in the Cotaxtla farm only 20 ha belongs to the LOAM soil it is assumed that the other 5 ha tilled belong to the neighbouring soil units (and thus have different characteristics), but workability limits and hydraulic properties used in the calculations are from LOAM soil.
Under the prevailing circumstances, at the farm scale, the workable periods calculated following the methodology will only be as useful or good as is the delimitation of the soil units that the textural and organic matter represent.
Most information on soils in the tropical area of Mexico is available as in this farm scale. Actions have to be made to locate and delimit the areas that this information represents in order to make a better use of the workable periods for tillage systems planning.

5.2.3 Broad (regional) scale

5.2.3.1 Description

The information on soils comes from 1 : 250 000 maps (INEGI, 1993) and information on slopes from a 1 : 50 000 map (INEGI 1988). Climatic maps are available at 1 : 1000 000 scale (INEGI, 1987). On the maps, soil units are delimited by the criterion of a soil type being present in more than 60% of the area. The soil units are named after the morphological, physical and chemical characteristics of the dominant soils. The texture is described only in terms of fine, medium or coarse. 'Representative' soil profiles are described quantitatively in terms of texture and organic matter content, and qualitatively in terms of structure. The delimited soil units are in spatial scales between 10^4 and 10^5 m so one described soil profile represents an area that will usually contain some other pedological soil types and textural classes as well. Apart from the lack of detailed soil physical information, the following problem arises at this scale for the modelling of the water balance: rainfall and evaporation data may only be available from the nearest climatic station, which could be more than 20 km away. According to Kim (1995), at larger scales (> 10^3 m) rainfall heterogeneity must be taken into account for water balance studies.
The spatial unit to be analysed at regional level is a large soil unit (up to 10 000 ha) delimited in the 1 : 250 000 soil map of the region currently available.
Taking into account the review of modelling the water balance in Chapter 5.1.1, no attempts were made in determining the water balance using the "representative" point data with the objective to represent the regional scale. Also,

when workability limits can be made available for the representative point, the calculated workable periods would be only valid for the nearby cropped area of that point.
As an example of the availability of the soil data at this scale, Figure 54 shows part of the central area of Veracruz of the soil map scale 1: 250 000 (INEGI, 1984) where the Cotaxtla Farm is located.

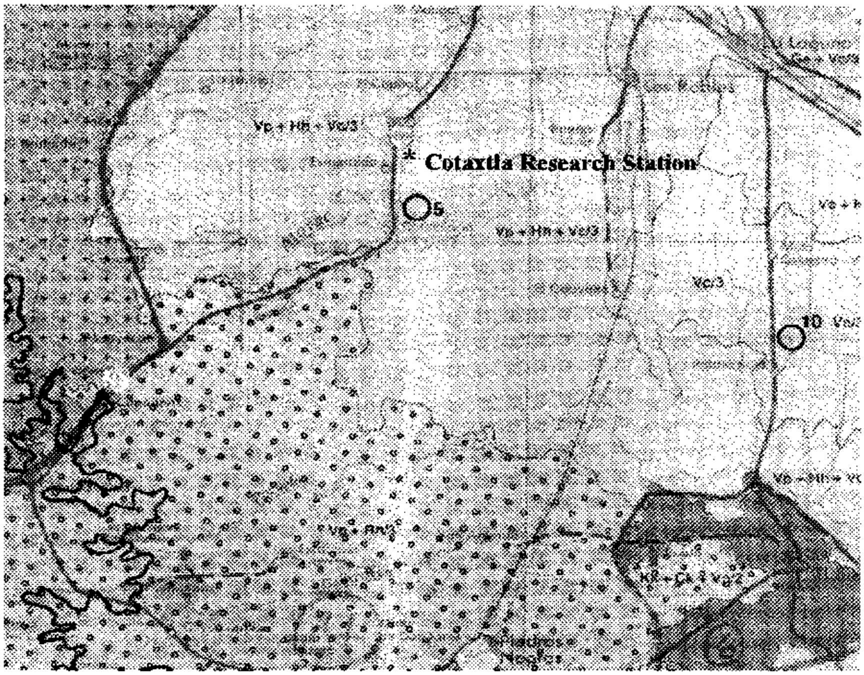


Fig. 54. *Location of the farm of Cotaxtla Station in the soils map 1:250 000 of the area under study (delimited fields and the farm were shown in Figures 50 and 53, respectively). The textural class of the soil unit where the farm is located is class "Fine texture".*

5.2.3.2 Example of calculation of workable periods at regional scale

The approach used by Uresti and Campos (1994) in the area under study is presented here. The methodology developed by these authors to calculate the workable periods includes the following:

Water Balance
The parameters used to calculate the water balance with the available data are:

- Soil texture from 0 to 30 cm depth (Broad textural classes; Coarse, Medium, Fine)
- Daily evaporation (mm)
- Daily precipitation (mm)
- Moisture characteristics (Field capacity, Permanent wilting point)
- Slope range
- Deep percolation (mm)
- Retention coefficient for the runoff

Workability Limits

The thresholds used are the consistency limits; plastic limit (PL) and shrinkage limit (SL).Those were defined for each of the three textural classes (fine, medium, coarse).

The calculations of workable periods were made for soil units delimited by the same three textural classes in the soils map scale 1: 250 000 (INEGI, 1984). Climatic data from the meteorological station "El Copital" (mentioned in the detailed scale) were used to calculate the workable periods for the soil unit where the farm of Cotaxtla station is located. The number of workable days came out as follows: 25, 9 and 8 respectively for the coarse, medium and fine textured soils, located in slopes of less than 5%.

For the calculation, a day was considered workable when the soil moisture in a depth from 0-30 cm (considered as one layer) is between the plastic and shrinkage limits (typical consistency data were used here for each of the three textural classes). The water balance is calculated daily using the rainfall and evaporation data in a series of ten years. Coefficients of runoff and deep percolation are considered according to slope and textural class. The workable days are averages from those found to occur during June and July. Over these ten year, using above assumptions, no workable days occurred during the month of May.

On the soils map of Figure 54 the farm of Cotaxtla Research Station is located in a soil unit of "fine" textural class (indicated as Vp + Hl + Vc/3 on the map). This is because the unit has as a dominant soil the Pelic Vertisol (Vp) and as secondary soil the Luvic Phaeozem (Hl) and Cromic Vertisol. The number 3 indicates fine texture. It is true that there are many fine soils in this area, but most are under grassland and not under cropping.

From indicated above, on average there are 8 days of workable condition in a soil profile of 0 to 30 cm depth (for the period May to July).

Table 10 shows the use of the information on the workable periods obtained at regional scale. Abovementioned authors have calculated the number of tractors (65 hp to 75 hp) required to perform the tillage operations within the workable period, in the 94 000 ha under cropping in the Agricultural District "DDR 007" in the central area of the State of Veracruz, where agricultural land lies in slopes between 0 and 5 %. Coarse, medium and fine textures are found in 30%, 40% and 30% respectively, of the mentioned area under cropping.

Table 10. *Available days and number of tractors (class 65-75 hp) required for tillage operations in the Agricultural District "DDR 007" Veracruz. (Uresti and Campos, 1994).*

Textural class	Available days (May - July)	ha/ tractor/crop cycle	Nr. of tractors required
Coarse	25	86	326
Medium	9	31	1225
Fine	8	28	326
Total			1877

5.2.4 Utilization of workability information at the different spatial scales

Field level

The extension of the methodology used at the experimental level (described in Chapters 3 and 4) can be used straightforward at field scale. If reliable PTF's, can be made available for more soil textural classes of the area under study, only textural and organic matter content information will be needed for the detailed scale, as is shown in the example of the LOAM soil.

Farm level

When it is possible to accurately delimit those areas (parts within a farm) as they are to be represented by the data on texture and organic matter content, then the methodology discussed in chapter 5.2.2 can be applied to obtain accurate information.

Regional level

At present, the methodology from chapter 5.2.2. can only be applied to the points where data on soil and climate are available. In that case it is possible to obtain a more realistic number of workable days than the current approach used in the area under study. Accurate information on workable periods at regional level can then be produced by aggregating the information that come out from the field and farm levels.

6 THE DEVELOPMENT OF A DECISION SUPPORT PROCEDURE

6.1 Automated analysis procedure

To arrive at useful parameters to support the planning of tillage systems, and to find the most suitable system for a field, farm or region, it is necessary to analyze a great deal of basic information (as it is shown in Fig. 1.1). Crop and environmental requirements, soil water status, workability limits, and available power are all factors that vary in the area under study. It would also be impractical and costly to generate specific recommendations *ad hoc* in view of the dynamic nature of most of the factors.

Analysis of this information requires the use of algorithms, models, data bases, rules and thresholds. It would be impractical and impossible for a final user such as an extension worker or farmer to make an analysis as is done in the research stage. To take advantage of the methodology developed to make workability information available, a systematic procedure for automatic analysis is necessary. where only the specific information from a site needs to be provided by the user. In this way, the analysis can also be repeated to visualize the results of using different initial conditions, and so to utilize the output as support for planning or the decisions to be made, also in view risk analysis.

6.2 Decision making procedures in agricultural engineering

According to Zohadie and Kok (1991), an expert system is a computer software system that is able to provide advice in a particular subject area equal in quality to that which could be provided by an acknowledged human expert. The philosophy behind expert systems is to use a personal computer to perform an analysis of information in a manner similar to that of a human expert (Plant et al., 1992).

According to Stomph and Fresco, (1991), the general structure of a decision making process has different sources of information that may or may not be contained in databases. In that case, the information from the sources is assessed by expert judgements and/or simulation modelling.

Agricultural Expert Systems (AES) are gaining recognition as technology transfer devices (Meyer, 1990). Nowadays, there is great need for reliable decision support systems for many aspects of agricultural management. There is a need, not only to find research solutions to production-management problems facing farmers, but also to make the technology transfer readily available to them. One approach for achieving this goal is to develop systems that assist non-experts in reaching expert conclusions (Mannering et al., 1988).

Morrison et al., (1989), state the following in their description of expert systems: "Recommendations from expert systems are based upon inputs from the user, outputs from external program algorithms, and results of if-then axioms and rules of inference derived from experts. The input process for the user is ideally simple and ease to use. The user establishes the local conditions and limitations of interest. External programs which contain established functional relationships, may be used to estimate values for properties or conditions. These programs may be simple or complicated and may use data sets and linked routines. the resulting values comprise a data set that a human expert could use as the basis for making decisions and recommendations."

Expert systems could comprise a complete framework for agricultural resource management as an operational tool for a decision support for a whole farm. For example, a framework is under construction to be used for the Great Plains area of the USA. It is being developed through modules which simulate and predict crop and animal production, water use, nutrient uptake, erosion (by water and wind) and quantities of nitrates and pesticides leached. The framework also includes appropriate databases, an economic analysis package, and an environmental risk assessment module that will evaluate various preselected management options (Ahuja, 1998).

Most expert systems developed tackle a specific part of the production system. Some examples follow. A region-level set of decision rules was developed to provide conservation tillage recommendations to farmers in the eastern Corn Belt of the USA. The expert system TESTOP was developed in order to help in decide which tillage system(s) will be the most appropriate and/or profitable for a given farming operation in which maize and soya beans are the principal crops (Mannering et al., 1988).

The expert system PLANTING was designed to systematically develop specifications for soil engaging components on conservation planters (Morrison Jr. et al., 1989). PLANTING is loaded with a soil and weather database specific to the user's area. Specifications such as crop, surface residue, size of plots, and slopes are provided by the user and then matched by the program to available planting machines as a guide to machine selection.

CALEX is an expert system shell that was developed for crop management decision support (Plant et al., 1992). The shell provides for efficient data entry and management and permits the integration of information from a variety of sources to develop crop management guidelines.

Saputro et al. (1991) developed an expert system to assist with chemical application decisions.

ALES is a computer program that allows land evaluators to build expert systems to evaluate land according to the FAO framework (Rossiter and Van Wambeke,

1991). Evaluators build their own expert system with ALES, taking into account local conditions and objectives. ALES is not in itself an expert system, and does not include in itself any knowledge about land and land use. It is a framework within which evaluators can express their own, local knowledge.
There are several computer packages for application of land evaluation in land use planning (Van Diepen et al., 1991). The main components of these evaluation systems are:

- A geographic information system with information on climate, land (including soil), land use, crop yields, use limitations, population, administrative divisions, etc,
- A database management system,
- Analytical tools (models) to assess physical land use performance under given technological conditions, and
- Analytical tools for evaluating the adequacy of alternative land use options for given socioeconomic or environmental goals.

6.3 Methodology to develop the decision support procedure

One of the aims of the work in this project was the development of a procedure by which information could be analysed systematically in order to determine workability based recommendations for performing tillage.
The proposed procedure has the structure of an expert system with the objective to providing advice on soil tillage, based on workability criteria for the tropical area of Mexico.
For the construction of the framework the steps in Figure 55 were followed.

(i) The first step in the procedure is to define the relevant objectives of tillage for a given condition (i.e. required aggregate distribution at planting depth for the establishment of maize. Information about the requirements of seedbed preparation according to the type of seed was available from the literature, and from the quantification of local judgement. The optimum period for planting was available from local research on crops.

(ii) The second step is to define the soil conservation requirements, local information about soil, terrain, and climate characteristics as well as land use and tillage systems may be analysed in search of the combination of factors (including tillage) that produces minimum soil losses.

(iii) The third step is to estimate the soil water status and workability limits. The data available about the soil and climate characteristics will be also used in a water balance model in order to predict the soil moisture status at the time (related to optimum dates for planting) tillage should be done. This has already been treated in Chapters 3 and 4.

(iv) The fourth step is to generate a database with the implements and power sources. The inventory of the power sources and implements determines the gross capacity of work available for doing the tillage operations.

6.4 Results and discussion

6.4.1 The knowledge base

By reviewing a set of rules that takes into account specifications for crop establishment and/or soil and water conservation, workable period and available power, an attempt will be made to find a tillage option and optimum working time that matches the specified conditions. So far, the procedure has been constructed for maize as a pilot study.
The knowledge base is constructed as follows:

1. *Crop-related information*

A data base of the seedbed requirements (in terms of aggregate size distribution at planting depth) and optimum planting dates for the local crops is available. Seedbed requirements are taken from the literature, and from research in the area under study by Campos, (1993) and Cadena et al, (1996).

2. Preliminary *recommendation of a tillage system based on soil conservation* requirements

Soil erosion is a problem in some farms in the area under study, and thus the recommendation of a tillage system based on soil conservation is important. In this part of the knowledge base, the methodology of Uresti et al., (1993) is used to calculate the soil losses under different crop management and tillage systems. The soil losses are calculated using the universal soil loss equation (USLE). The values of the parameters of this equation are based on research carried out by the same authors in central Veracruz, Mexico. A threshold of permissible soil losses for the area under study (considered also by Uresti et al., 1993 according to local soil types, depth and the erosion-productivity relationship) is used to compare the calculated soil losses in each situation. By simulating different mechanical practices for erosion control, conditions of crop management and/or tillage systems, it is possible in this part of the process to arrive at one combination of these factors where annual soil losses are under the threshold value.

3. Recommendation of a tillage system based on *timeliness*

In this part of the knowledge base the available days for tillage are calculated.

This is accomplished by running SWATRE to perform the water balance and comparing the daily moisture status in the soil profile with the workability limits. The optimum time available combined with the area to be worked gives the work rate (h ha^{-1}). Then the work rate is compared with the gross capacity of work of the power source (from local data) working in an specified tillage system, which in first instance should be that one preliminary recommended in the first part of the knowledge base, which is based on soil conservation. The program calculates how much land can be tilled in the optimum time. When not all the land can be tilled in the available time, a warning message appears and with invitation to simulate another scenario using another tillage system and/or increasing the size of power source. The user can arrive at a power source-tillage system combination which meets timeliness objectives.

6.4.2 The inference mechanism

The inference mechanism, or expert system shell, is the part containing general problem solving logic (inference engine). An attempt was made to use some of the shells available (i.e. ALES, PROLOG). But it was not possible to adapt the procedure to those shells. It was decided that an inference mechanism could be created by using PASCAL. A computer program was made in this language in order to automate the procedure.

6.4.3 Flow chart and description of the computer programme.

In Figure 55 the flow chart of the computer program is shown. This was built to automate the decision support procedure. This is the initial version, where the analysis of information can be done using the scales of detailed and semi-detailed information.
The description of the computer program is presented in Annex 3.

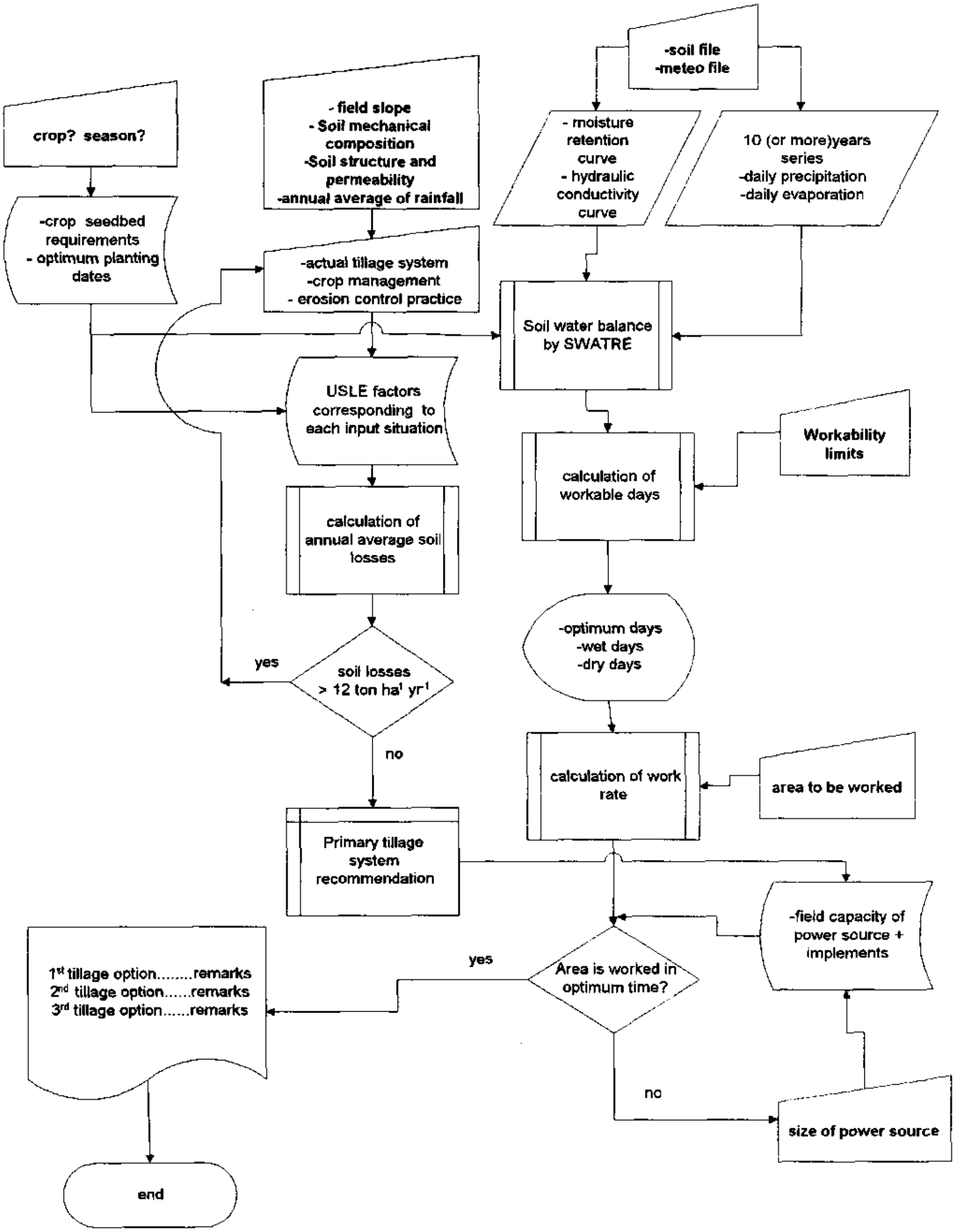


Fig. 55. *Flow chart of the programme forming the decision support procedure.*

7 CONCLUSIONS

Based on the hypotheses posed in Chapter 1.4 and after the results and discussion of the work carried out in this thesis, the following general conclusions can be drawn.

The in-field workable range of three soils representative of the tropical area of Mexico (namely LOAM, CLAY and SAND) was delimited as follows:

a) The optimum and sub-optimum results from the final operation of seedbed preparation (crumbling by harrowing) were quantified. The limit of the workable range in moist soil (for the LOAM and CLAY soils) corresponds rather well with the empirical threshold (plastic limit) of change in soil consistency from plastic to friable. The limit of the workable range in dry soil does not correspond to the empirical threshold (shrinkage limit) of change of soil consistency from friable to solid-rigid. The change from optimum to sub-optimum results occurred at a moisture content clearly above the shrinkage limit of the two soils mentioned. For the coarse textured soil, the optimum technological result can be attained at almost any moisture content.

b) The minimum energy necessary for achieving the required loosening and crumbling of the soil was quantified. The range where minimum energy goes together with achieving the aimed result is very narrow, at the lower end of the optimum moisture content range.

By means of relatively simple laboratory tests, the field thresholds can be quantified well in terms of the soil water-potential at which optimum and sub-optimum effects occur. Such are: damage of soil structure by compaction in the moist soil condition because of the process change from strength hardening to plastic flow. The same holds true for the dry condition because of the change from a crumbling process at planting depth to little or no desegregation (and thus very coarse MWD), using the same specific energy input.

The close relationship between the field workable range and the laboratory tests, allows a relatively simple but quantitative methodology to establish the workable range for the soils in the tropical area of Mexico. This is very important because: a) current problems of high energy expenditure and high costs of soil preparation are due to the use of subjective criteria about the soil moisture condition when tillage has to be performed, and b) current planning of tillage systems and calculation of workable periods at a larger planning scale is done by delimiting the optimum state of soil for tillage using the empirical thresholds of the plastic limit and the shrinkage limit.

The use of a mechanistic model for the calculation of the water balance, combined with the soil workability information, allows a detailed analysis of the workable status of the soil profile. This is done not only to better account for the duration of workable periods, but also to indicate at which depth in the profile this situation occurs. With this information it is possible to design (plan) a tillage system (implements and power sources) that can be operated giving the best results, matching the time, depth, area and quality of the growing environment for crop establishment.

The methodology developed in the experimental field and the laboratory can be applied at field (detailed) scale, where it is possible to make available a complete set of the required data. It could be extended to farm (semi-detailed) scale where the soil hydraulic characteristics required to calculate the water balance with a deterministic model, can be predicted from limited texture and organic matter content data, by means of pedotransfer functions (PTF's).

FUTURE WORK

The foundation has been laid for an automated procedure for the analysis of data (including soil workability) in different scenarios in order to arrive at information that can be used as a support for the tillage system and mechanization planning. However, it is clear that this process requires further development. Analysis systems for advisory or decision support purposes such as this one have to be improved according to the feedback after tests with data from different conditions in the region where it is to be applied, and requires a multi-disciplinary team involved in its development.

Most of the soil information in the tropical area of Mexico is available only in terms of texture and organic matter content. To use this information to calculate the workable periods for planning tillage systems at specific areas the following actions must be made:

a) To validate the use of the PTF's from the Staring Centrum (Stolte et al., 1996) for other medium textured soils of the region, and to make further assessments of these PTF's with fine textured soils.

b) To georeference the existing information on texture and organic matter content (to establish the location and area that the information represents), and parallel to establish the workability limits to samples at each location with the laboratory tests, then try to establish relationships between workability limits and textural and organic matter information. This in order to develop a PTF (similar to Terzaghi et al., 1988) that estimates the workability limits for other places of the region under study using just textural and organic matter information.

The technical selection and planning of optimum tillage systems in the area based on workability information has to be supported as well for other than technical aspects. The social acceptance and economic benefit of tillage alternatives in the medium and long term must be analyzed.

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SUMMARY

In the tropical area of Mexico, when and how to carry out tillage is a qualitative decision taken by the farmer. There is no quantified information about the interaction between a chosen process of cultivation, soil type and weather, which dictate the tool and power requirements. Waste of energy and soil degradation by erosion and compaction, and lack of timeliness are recognized problems caused by inadequate tillage management in the tropical area of Mexico.

In this thesis, the workable range of soils was quantified in the field, and the limits of that range, represented in the laboratory by tests to soil samples. This information is the basic part of a soil workability based procedure which is developed as a decision support tool for selecting specific tillage practices. The methodology was conceived for application in the tropical area of Mexico. For this reason a description of the area under study in relation to the present agricultural production system, including tillage related problems, was presented in Chapter 2 .

In Chapter 3, the field and the laboratory studies to quantify the workable range of soils in the area, were treated. The methodology and results from those studies were presented and discussed, considering the technological result of the tillage operation and the input of energy at a range of soil moisture contents. Empirical relationships between initial moisture content and the technological result of tillage showed that results from loam and clay soils changed from optimum to sub-optimum at soil water potentials that rather coincide with the plastic limit in relatively moist soil. As soil was drying out, the implement result changed from optimum to sub-optimum at soil water potentials well below to that for the shrinkage limit, so the actual field work was smaller than the theoretical friable range of the soils. The minimum input of specific energy to obtain optimum results was close to the soil water potential, where results changed to sub-optimum as the soils where drying out. Observations in a sandy soil indicate that required technological result is attained at almost any moisture content.

The thresholds that delimit the optimum and sub-optimum results in the field are represented by means of laboratory tests, an air permeability test (for the wet limit) and a drop test (for the dry limit). The methodology as developed here, and results from laboratory experiments are presented; links and discrepancies in representing field results were discussed. The thresholds established by the results of the laboratory tests agree well with the findings in the field. This enables the establishment of workability limits in terms of soil water potential for other soils in the area by means the mentioned laboratory tests.

Once the workable range of a soil is known, whether this status is present on time (during the workable period within the cropping calendar) depends on the

interactions between soil characteristics and weather. In Chapter 4, the possibilities to model the soil-water balance in order to obtain the relevant information for tillage planning and operation, and the data required to do this, was discussed. The possibility of use PTF's (pedo-transfer functions) for deriving the hydraulic characteristics of soils from limited textural data normally available in the area under study was explored, as they are required by deterministic soil-water models. It was found that PTF's developed in The Netherlands estimate well the hydraulic characteristics for the loam soil of the area under study.

The soil workability and the soil-water balance are the 'tools' to calculate the workable periods, but in this area the data available to determine both 'tools' is available at different spatial scales. The possibility of extending the methodology applied at the experimental field level to other scales and the use of workability information for operational decisions and planning was discussed in Chapter 5.

To decide objectively which tillage practice will be chosen and when tillage should be carried out, a great deal of information has to be analysed. To take advantage of the soil workability methodology developed, it is possible to apply an automated procedure where the user only needs to supply site-specific information, and where relevant information to utilize as support for planning decisions is provided. In chapter 6 an initial version of such an automated procedure was presented.

General conclusions based on this study, regarding the development and use of the methodology on soil workability to support the planning and operation of tillage systems, are finally given in Chapter 7.

RESUMEN

En el área tropical de México, como en muchas otras regiones del país, las decisiones de cómo y cuándo realizar las operaciones de labranza se toman en forma cualitativa. Hasta el momento no existe información acerca de la interacción entre los procesos de labranza, y los tipos de suelo y clima, pese a que esta determina el tipo de herramienta y fuente de potencia requerida.

En esta tesis, el rango de "laborabilidad" de los suelos (*franco, arcilloso y arenoso*) del área tropical del país fueron cuantificados en campo, y los límites de ese rango pudieron ser representados por medio de pruebas de laboratorio relativamente simples. Esta información es el componente básico de un proceso de apoyo para tomar decisiones que está siendo desarrollado como una herramienta para apoyar en la selección adecuada de prácticas de labranza. La metodología fue concebida para ser aplicada en las condiciones de las zonas tropicales de México. Por esta razón, en el Capítulo 2 se presenta una descripción de los sistemas de producción del área de estudio, donde se incluye la labranza y la problemática relacionada a esta actividad.

En el Capítulo 3 , se describen y discuten los trabajos de campo y laboratorio realizados para cuantificar el rango de "laborabilidad" de los suelos del área. La metodología y resultados son presentados y discutidos considerando el resultado tecnológico de las operaciones de labranza y la aplicación de energía a diferentes contenidos de humedad en el suelo. Relaciones empíricas fueron obtenidas con el fin de poder cuantificar límites en términos de potencial mátrico del suelo a los cuáles el resultado (y el proceso) de la labranza cambia. Los resultados muestran que para los suelos *franco y arcilloso*, los resultados cambian de óptimo a subóptimo a potenciales mátricos que coinciden con el límite de plasticidad en suelo relativamente húmedo. Conforme el suelo pierde humedad, los resultados de las operaciones de labranza cambiaron de óptimo a subóptimo a potenciales mátricos bastante menores que el límite de contracción establecido, por lo que el rango actual de "laborabilidad" fue menor que el rango friable teórico para estos suelos. La mínima aplicación de energía específica para obtener el mejor resultado tecnológico de la labranza fue cercana al potencial mátrico, en el que los resultados cambiaron a subóptimos conforme los suelos se secaban. Observaciones en suelo *arenoso* indican que un resultado tecnológico de labranza adecuado se obtiene casi a cualquier contenido de humedad.

Los umbrales que delimitan los resultados óptimos y subóptimos en el campo están representados por medio de pruebas de laboratorio; esto es permeabilidad del aire (para el límite húmedo) y prueba de caída de agregados (para el límite seco). La metodología y resultados de laboratorio también se muestran, y se discute su relación y discrepancias desde el punto de vista de su utilidad para representar los resultados de campo. Los límites establecidos con las pruebas de laboratorio concuerdan con los resultados de campo. Esto permite que los

limites de "laborabilidad" para otros suelos en el área puedan ser establecidos en términos de potencial mátrico del suelo.
El Capítulo 3 fué la parte principal del trabajo de tesis, pues es el desarrollo de la metodología para caracterizar el rango de "laborabilidad" de los suelos en el área de estudio.
Una vez que el rango de "laborabilidad" es conocido, es necesario conocer por cuánto tiempo esta condición está presente (principalmente durante las fechas de establecimiento del cultivo), y esto depende de la interacción del suelo y el clima. En el Capítulo 4, se discute qué datos son necesarios para realizar el balance de humedad en el suelo y obtener información relevante para la planeación y operación de la labranza. La posibilidad de usar funciones de transferencia de propiedades de suelo (FTPS) para derivar características hidráulicas de los suelos, usando información limitada a textura y materia orgánica fué explorada. Esto debido a que esta información tan limitada de suelos es la que está normalmente disponible en el área de estudio. Se encontró que FTPS desarrolladas en Los Países Bajos estimaron bastante bien las características hidráulicas del suelo *franco* del área de estudio.
El rango de "laborabilidad" del suelo y el balance de humedad son las "herramientas" para calcular la cantidad de días óptimos disponibles para realizar la labranza. En el área de estudio, los datos para determinar las mencionadas "herramientas" se encuentran disponibles a diferentes escalas en el espacio. En el Capítulo 5 se discute la posibilidad de extender a las otras escalas la metodología que se aplicó a nivel campo experimental (parcela), así como el uso de la información de "laborabilidad" que se obtenga para la planeación y operación de sistemas de labranza.
Para decidir objetivamente qué práctica de labranza seleccionar y cuándo realizarla, es necesario analizar una gran cantidad de información. Para tomar ventaja y utilizar la metodología desarrollada acerca de la caracterización del rango laborable de los suelos, ésta debe usarse como parte de un procedimiento de análisis que debe ser automatizado. Esto de tal manera que el usuario solamente deba proveer al sistema los datos específicos de su localidad y, después del análisis automatizado, obtenga información relevante que le sirva de apoyo para tomar sus decisiones de planeación y/o selección del sistema de labranza. Por ello en el Capítulo 6, se presenta el desarrollo de una versión inicial de un sistema automatizado de análisis.
Finalmente,en el Capítulo 7, se presentan las conclusiones generales en cuanto al desarrollo y uso de la metodología en la "laborabilidad" de suelos para apoyar la toma de decisiones en la planeación y operación de sistemas de labranza. Estas son basadas en el análisis y discusión de los resultados, teniendo como referencia las hipótesis planteadas inicialmente.

SAMENVATTING

In het tropische deel van Mexico wordt de beslissing over het uitvoeren van de grondbewerking (tijdstip, manier waarop) gebaseerd op kwalitatieve gegevens. Er is geen kwantitatieve informatie beschikbaar over de interactie tussen het gekozen grondbewerkingssysteem, het bodemtype en het heersende weertype, parameters die in principe de werktuig parameters en de energiebehoefte bepalen. Verspilling van ingezette energie, tekort aan beschikbare tijd en bodemdegradatie door erosie en compactie zijn duidelijke problemen veroorzaakt door niet effectief management.
In dit proefschrift is het vochtgehalte traject waarin grond bewerkbaar is, bepaald via veldproeven en gestandaardiseerde testprocedures in het laboratorium. Dit is de basis van een procedure gebaseerd op het bepalen van de bewerkbaarheid, met als doel een beslismodel te ontwikkelen wat gebruikt kan worden voor de selectie van grondbewerkingsactiviteiten of -systemen, geschikt voor toepassing in het tropische deel van Mexico.
Een beschrijving van de landbouw, het gebruikte productiesysteem in het studiegebied en de daaraan gekoppelde problemen met grondbewerking is behandeld in hoofdstuk 2.
In hoofdstuk 3 zijn de veld- en laboratoriumstudies, met als doel het bepalen van bewerkbaarheidgrenzen van representatieve gronden in het studiegebied behandeld. De toegepaste methodologie en de resultaten van de uitgevoerde studies worden behandeld en getoetst aan het technologische resultaat van de grondbewerkingshandeling en het energie gebruik over een reeks van vochtgehaltes. Empirisch gevonden verbanden tussen het vochtgehalte en het technologische resultaat van grondbewerking gaven aan dat het omslagpunt aan de 'natte' kant van het traject, waarbij de resultaten voor de bestudeerde lemige en kleiige gronden nog acceptabel zijn, goed samenvallen met de uitrolgrens. Aan de 'droge' kant van het traject werd het resultaat niet meer als acceptabel beschouwd bij vochtgehaltes die hoger lagen dan de krimpgrens. Dit betekent dat het traject waarin daadwerkelijk optimaal bewerkt kan worden kleiner is dan het theoretische traject zoals bepaald via deze consistentie-grenzen. De minimum energiebehoefte werd gevonden bij vochtgehaltes rondom de bewerkingsgrens aan de 'droge' kant van het traject. Voor een zandige grond bleek dat het gewenste resultaat onder bijna elk vochtgehalte behaald kan worden.
De bewerkbaarheidsgrenzen zoals toepasbaar in het veld kunnen worden bepaald door laboratoriumproeven, en wel met de luchtdoorlatendheidstest voor de 'natte' kant, en met een valproef voor de 'droge' kant. De ontwikkelde methodologie, de resultaten van deze laboratoriumproeven en de relatie tot de veldproeven zijn eveneens behandeld in dit hoofdstuk.

De resultaten van de laboratoriumproeven komen goed overeen met de veldwaarnemingen. Dit betekent dat hiermee bewerkbaarheidsgrenzen (uitgedrukt in vochtspanningen) kunnen worden bepaald voor andere gronden in de omgeving.
Het voorkomen van bewerkbare perioden gedurende de maanden dat de inzaai voorbereid kan worden, hangt geheel af van het weer en de bodemeigenschappen. In hoofdstuk 4 is beproken op welke manier de water balans bepaald kan worden (met als doel de planning van grondbewerkings-activiteiten), en welke gegevens hiervoor benodigd zijn.
De mogelijkheden om hier zgn. 'pedo-transfer functies (PTF's)' toe te passen, zijn onderzocht. Met behulp van deze functies kunnen de hydraulische karakteristieken van de grond (welke nodig zijn om een water-balans model te kunnen toepassen) worden bepaald uit beperkte textuur gegevens. PTF's zoals in Nederland ontwikkeld bleken vooral voor de lemige grond goed toegepast te kunnen worden.
De combinatie van het bepalen van de bewerkbaarheidsgrenzen en het simuleren van het vochtgehalte en -verdeling in het profiel vormt het middel om werkbare dagen te kunnen bepalen. De beschikbaarheid van data in dit deel van Mexico is echter afhankelijk van de ruimtelijke schaal waarin gewerkt wordt. In hoofdstuk 5 zijn de mogelijkheden om de methodologie ontwikkeld op (proef)veld schaal te extrapoleren naar andere schalen, behandeld. Met name de geringe bodemfysische informatie van bodemkaarten legt grote beperkingen op bij het bepalen van werkbare perioden.
Ten einde op een objectieve manier te komen tot het beste grondbewerkings-systeem en de bepaling van het tijdstip waarop grondbewerking kan worden toegepast, is het noodzakelijk dat er veel informatie wordt geanalyseerd. Echter, gebruikmakend van de methodologie om bewerkbaarheidsgrenzen te bepalen, kan er een geautomatiseerde procedure (beslismodel) ontwikkeld worden waarbij de gebruiker slechts de plaatselijk relevante informatie invoert en daarmee een advies ontvangt, gebaseerd op bijvoorbeeld teeltkundige en bodem- en water conservering criteria. In hoofdstuk 6 wordt de eerste opzet van een dergelijk model behandeld.
Hoofdstuk 7 geeft tenslotte de belangrijkste conclusies van deze studie aan.

Curriculum Vitae

Martin Cadena Zapata was born on February 1st 1961 in Parras, Coahuila (Mexico).
From 1978 to 1983 he studied for a BSc degree at the Agricultural University Antonio Narro in Saltillo, Coahuila (Mexico). Main subject Agricultural Mechanization.
During 1986-87 he studied Agricultural Engineering at Silsoe College, Faculty of Cranfield Institute of Technology (U.K.) where he obtain an MSc degree in Soil and Water Engineering. In 1991 he followed a 9 month course on Agricultural Machinery Design at the Tsukuba International Agricultural Training Centre (Japan).
From 1994 to 1998 he was enrolled in the PhD programme of Wageningen Agricultural University (The Netherlands) to obtain a PhD degree carrying out research in Soil Tillage, in the tropical area of Mexico.
From 1983 up to date he has been working as researcher in the Agricultural Engineering Unit of the National Institute for Forestry, Agricultural and Livestock Research (INIFAP) at Cotaxtla Research Station, Veracruz, Mexico.

Annex 1

POWER SOURCES AND IMPLEMENTS

Tractor.
Massey Ferguson MF 285 rated power 53 kW at 2000 rpm at flywheel.

Disc plough.
John Deere JD 3635 of three point linkage category II. Three plain discs of 710 mm diameter and 4.79 mm thickness. Weight 570 kg.

Disc harrow.
Massey Ferguson MF 35 of three point linkage category II. Twenty plain discs of 559 mm diameter and 3.9 mm thickness. Weight 610 kg.

No till planter.
This is a prototype from INIFAP to be operated by tractor. Soil engaging tools are a bubbled disc and a chisel.

Oxen.
A pair of animals, body weight: 700 and 850 kg.

Plough.
Mouldboard plough for animal traction of 25 cm cuttting width.

Annex 2

Analysis of variance of the Mean Weight Diameter (MWD) of aggregates distribution at planting depth after harrowing for soil LOAM.

Source of variation	Degrees of freedom	Mean square	$F_{calculated}$	$F_{tabulated}$ (0.05)	$F_{tabulated}$ (0.01)
Soil moisture	5	151.5	20.3	2.9	4.5
Error A	15	7.4			
Tillage system	1	2436.7	356.1	4.4	8.2
Interaction	5	142.9	20.8	2.7	4.2
Error B	18	6.8			

Analysis of variance of the total energy expenditure (kW.h.ha) for two tillage systems (conventional and no-tillage) for soil LOAM.

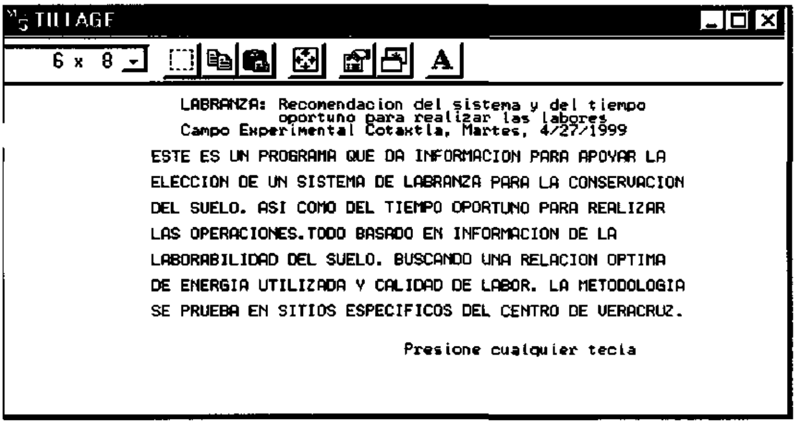
Source of variation	Degrees of freedom	Mean square	$F_{calculated}$	$F_{tabulated}$ (0.05)	$F_{tabulated}$ (0.01)
Soil moisture	5	3482.6	55	2.9	4.5
Error A	15	63.1			
Tillage system	1	110167.1	1543.9	4.4	8.2
Interaction	5	3213.2	45	2.7	4.2
Error B	18	71.3			

Annex 3

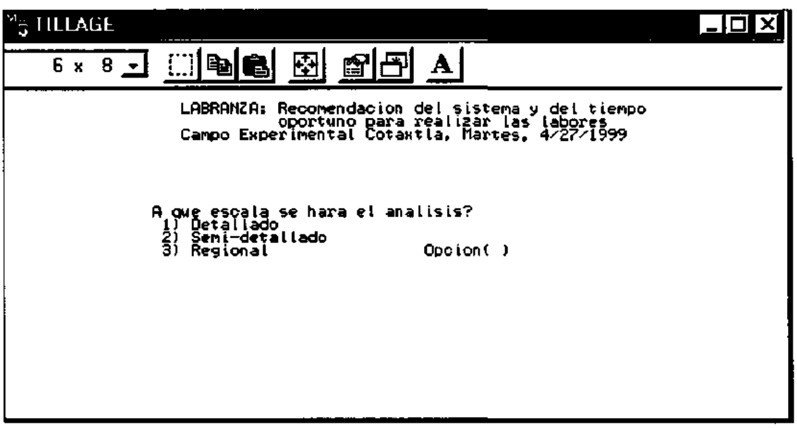
Description of some parts of the programme

INTRODUCTORY MODULE

At the start, an explanation appears in the screen about the aim of the programme, and about the procedure on how to obtain information to support tillage decisions.

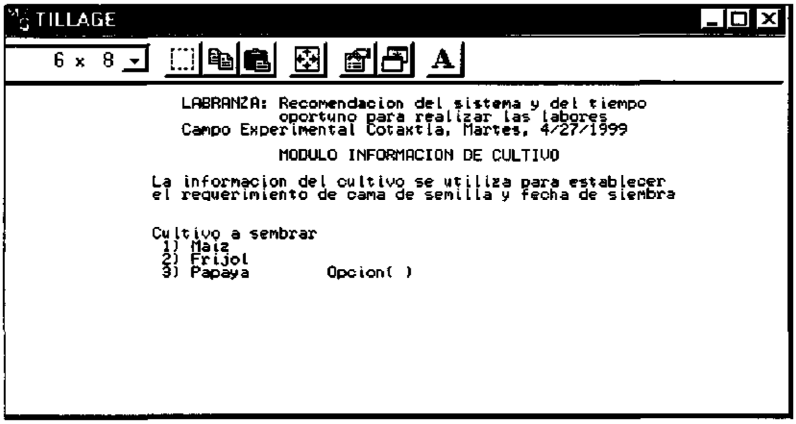


The following screen asks about the spatial scale at which the analysis has to be performed. At the moment only the detailed (Field) and semidetailed (Farm) scales are available.



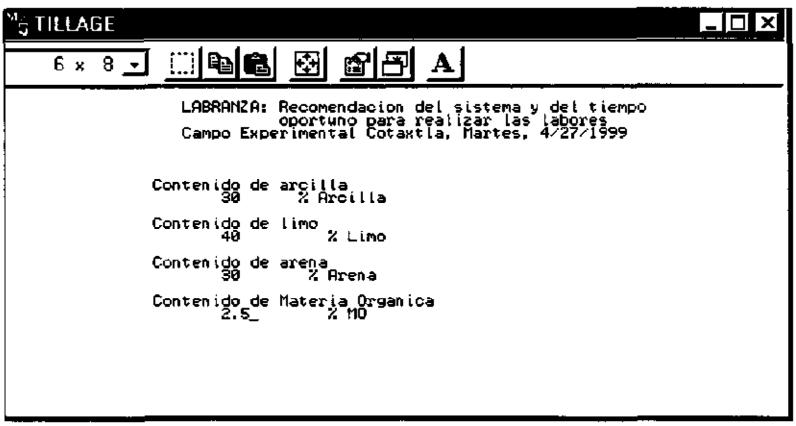
CROP INFORMATION MODULE

The name of the crop is requested. As a result, a file with information about seedbed requirements as well as the optimum dates for establishment is requested. In this example, the crop used is maize. Information on other crops can be added as it will become available.

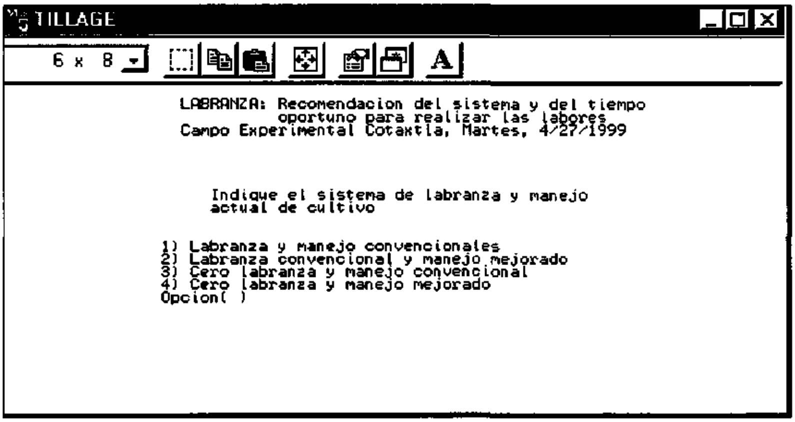


SOIL LOSS CACULATION MODULE

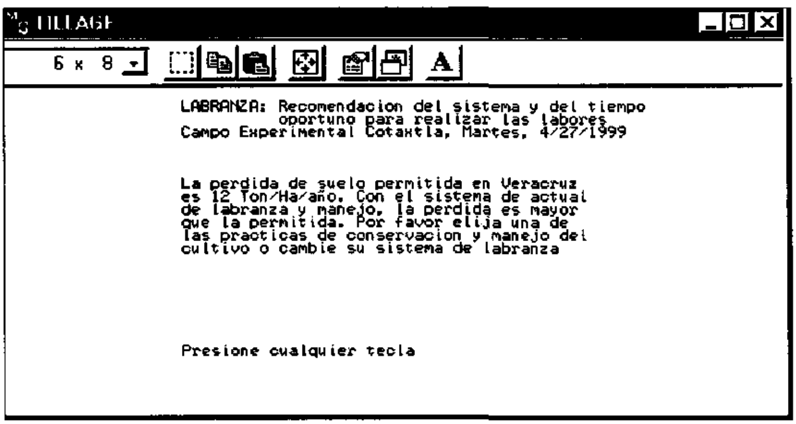
In this part of the programme, the actual tillage system together with the environmental information is used to calculate the soil losses using the USLE. The user has to provide information such as slope degree and length, texture, organic matter content, annual amount of rainfall. The information is entered in several screens; as an example the screen for entering information on soil structure is shown.



The tillage system currently used also has to be indicated, as well as the crop management. The user can choose from those available in the screen menu. When more tillage options become available, they can be added to the menu. The user is also asked if a practice for erosion control is being used. Several options are in the screen menu for the simulation of different scenarios.

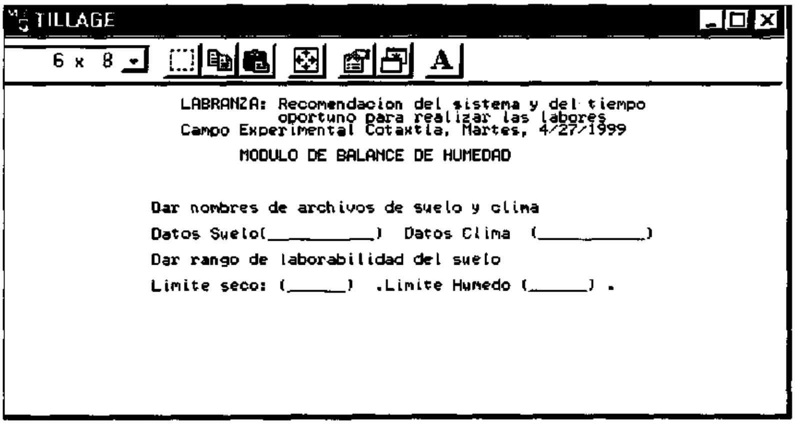


When all the information mentioned before is provided, the programme calculates the soil losses for the conditions specified. A warning message appears in the screen when the calculated losses are higher than allowed. In that case the user is invited to assess other scenarios by choosing other combinations of tillage, crop management and/or erosion control practices. When soil losses are lower than the threshold level, this is indicated and the programme continues.

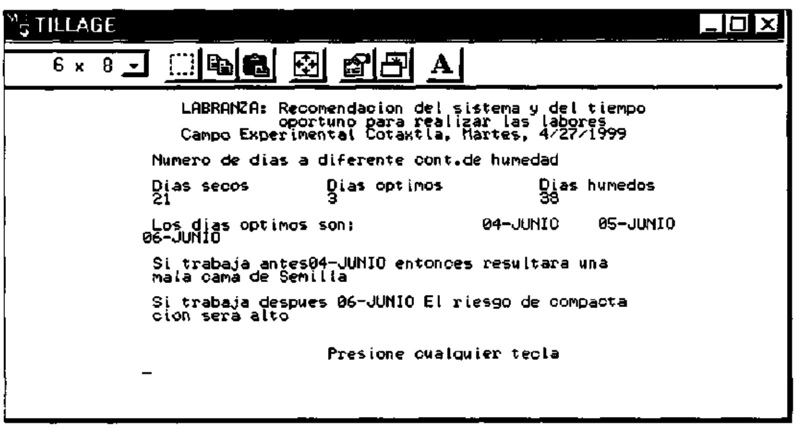


WATER BALANCE CALCULATION MODULE

In order to calculate the water balance, the names of the data files containing the soil and climatic information should be provided. The workability limits of the soil also have to be given. Once information is complete, the programme links to SWATRE and calculates the water balance.

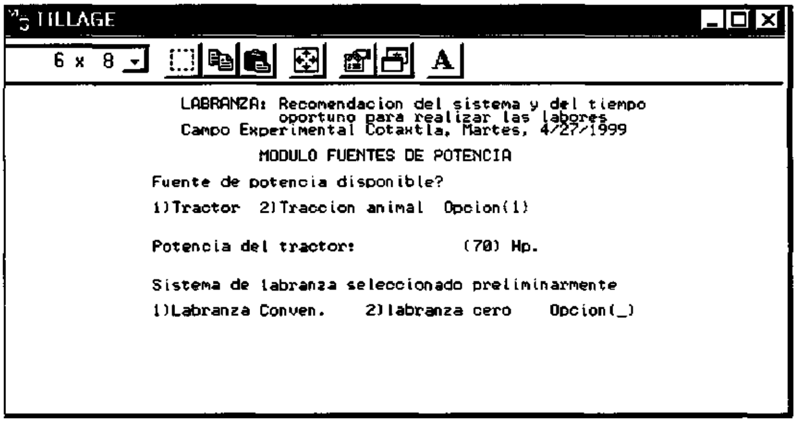


The programme checks on a daily basis during the period when tillage must be done whether the moisture content of the soil is within the workability limits. Then the number of dry, optimum and wet days are given and the dates of the optimum days are shown. A message appears, warning that the results of tillage may be poor if carried out in suboptimum conditions (during dry or wet days).



POWER SOURCES MODULE

At this point the programme calculates the required rate of work using the optimum period and the area to be tilled. The user is asked to give the type of power source available and the primary tillage system to be used. As a first choice, the tillage system should be the one recommended according to the soil conservation criteria. At this moment only conventional tillage and no-till are available. Other options can be added when they become available.



At the end, the programme displays information with the area that can be worked in the optimum period with the tillage system chosen and available power indicated. If the total area cannot be tilled in the optimum time, a message appears inviting the user to try another scenario by either increasing the power source or changing the tillage system.