SOIL MANAGEMENT FOR IMPROVEMENT OF SOIL PHYSICAL CHARACTERISTICS RELATED TO EROSION IN URUGUAY

Promotor: Ir. U.D. Perdok, hoogleraar in de grondbewerking

SOIL MANAGEMENT FOR IMPROVEMENT OF SOIL PHYSICAL CHARACTERISTICS RELATED TO EROSION IN URUGUAY

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STATEMENTS

1. In the short term, the positive effects obtained on soil physical properties by the incorporation of crops as green manures exceed those obtained by reduced tillage systems. *(This thesis)*

2. It is possible to assess the soil quality with respect to risk of erosion by quantifying a number of simple and compound soil characteristics. *(This thesis)*

3. The presence of an argillic B horizon is the main constraint in some Uruguayan soils for water movement in the profiles. *(This thesis)*

4. The sealing index expressing the ratio of the saturated hydraulic conductivity of an unsealed sample to that of a sealed one of the same origin is a good tool to evaluate the risk of crust formation. *(This thesis; Roth, 1992)*

5. The use of the chisel plough shows positive effects in soils having very poor physical conditions. The bulk density is lowered, as well as the resistance to penetration, and the rates of infiltration are increased. *(This thesis)*

6. In Uruguay the assessment of physical status of the soil would be necessary as a guide for soil management together with the design of soil conservation measures such as contour lines. The joint efforts would lead to a real conservation of the resource.

7. Innovative cropping systems, such as the inclusion of deep-rooted companion crops, trees and symbiotic legumes into traditional cropping systems, coupled with effective residue management, erosion control and improved tillage practices must be developed in order to retard soil degradation. *(Woomer et al., 1994)*

8. There are two fundamental components that have the greatest influence on decisions: the farmer's production objectives, and his/her perception of the consequences of various courses of action. *(Keeney, 1982)*

9. Research in poor countries suffers from several well-known deficiencies (funds, infrastructure, communication, etc.) but these are sometimes aggravated by conflicting concepts proposed by scientists, politicians, communities.

10. Is it necessary in advertising job vacancies to encourage women to apply? Wouldn't it be better if they were really considered under equal terms?

11. In bee hives, the labourers are pathetic. To defend themselves they must die.

12.

El final no tiene fin	Het slot heeft geen einde
ni tuvo inicio el comienzo	en het begin is nooit begonnen
yo vivo siempre en camino,	mijn leven is één onderweg
así lucho, quiero y pienso	zo strijd ik, zo heb ik lief, zo denk ik

Daniel Viglietti (Uruguayan poet)

Ana Terzaghi
Soil management for improvement of soil physical characteristics related to erosion in Uruguay.
Wageningen, November 13, 1996

a mi padre
a Emilia

ABSTRACT

Terzaghi, A. (1996)

Soil management for improvement of soil physical characteristics related to erosion in Uruguay. Ph.D. thesis, Department of Soil Tillage, Wageningen Agricultural University, The Netherlands, pp. 164, 32 fig., 27 tables, 182 ref.

In Uruguay various soil physical characteristics are studied in three field experiments and by means of several laboratory analyses in order to relate those characteristics to the ability of the soils to resist the impact of rainfall erosion. The top layer is characterized by measuring several indicators of structure quality and the results are related to the behaviour with respect to rainfall, either natural or simulated. The subsoil is studied mainly on its hydraulic properties, since they are a constraint for water movement. Modelling of rainfall redistribution in layered profiles is used to obtain fast predictions of water behaviour when soil characteristics are varied. Based on the above analyses and simulations, we define limits that allow to assess the ability of the soil to resist erosion. The characteristics found to be most relevant are i) the presence of an argillic B horizon, ii) the susceptibility for crust formation expressed by a sealing index, iii) the stability of structure expressed by the wet sieving diameter and iv) the arrangement of aggregates expressed by the total porosity. Once the quality of the soil is known, the appropriate management has to be selected according to the limiting factors. A soil of medium quality can be improved by reduced tillage systems together with cover crops to be incorporated as green manures. When the quality is low, tillage intensity cannot be reduced yet. Chiselling has to be considered together with crop incorporation. From our research, the improvement of physical conditions of the B horizon has been shown as highly relevant, and it needs to be studied further by means of deep chiselling or subsoiling together with crops especially adapted to deep rooting through the limiting layer.

Additional keywords: tillage systems, soil water modelling, quality index

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1 INTRODUCTION

This research aims at evaluating the mechanisms and degree of changes in soil physical properties by soil management and at determining to what degree these changes influence rainfall erosion. It attempts not only to qualify but also to quantify those effects, in order to identify threshold soil characteristics determining erosion risk.

A better understanding is expected of the processes involved in changing the physical condition of the soil by tillage and crop management, thus allowing recommendations to be made to farmers. Soil physical condition is directly related to erodibility, and thus one of the main factors determining its quality for sustained crop production purposes. The definition of a set of simple laboratory and field procedures is sought, in order to assess the suitability of a certain soil in undergoing different management systems, considering the ability of that soil to prevent damages by rainfall erosion.

Erosion caused by rainfall has increasingly been a problem in the northwestern region of Uruguay, where this research was conducted. Continuous agriculture has brought considerable damage to this region, prior to the development and introduction of adequate control methods. The damage is manifest in the occurrence of visible sheet erosion, decreased yield of crops, increasing need for fertilizers, filling up of farm waterways, water reservoirs and even of streams. Some of these effects are shown in Fig. 1.

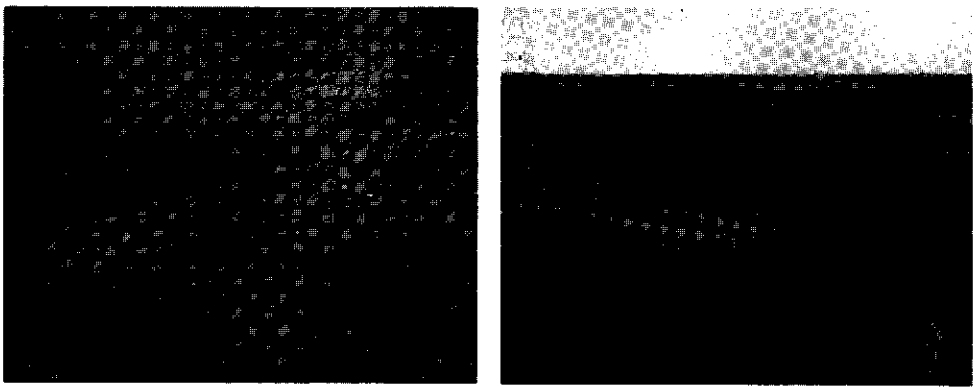


Fig. 1. *Visible evidence of erosion in Paysandú, Uruguay.*

In some severely eroded areas, rills and gullies are frequent. The general tendency is to start control measures only once erosion has already begun. Most of the times, these control measures are not effective since they do not aim at correcting basic errors linked to soil management and/or tillage activities. The status of the soil physical properties is mentioned as a main cause of soil erosion in agricultural areas of the country, but actual evaluation has not been done.

The Soils Division of the Ministry of Agriculture and Fisheries in Uruguay has been responsible for the soil surveying of the country, and since around 1970, for studying the causes of erosion as well as defining the control measures to prevent further soil losses. In 1978 a description of actual erosion in the country was published (Cayssials et al., 1978), based on aerial photo-interpretation. It described a general procedure to be followed in order to prevent erosion, based on the experience and visual observations of a group of agronomists and advanced farmers. They stressed the need for research leading to a better knowledge of the soil - management - erosion relationship. Petraglia et al. (1982) presented another description of the erosion situation in the country, based on observations. They demonstrated the partial adoption of erosion control measures such as grass strips and/or terraces. From this time on, researchers focused their studies using the Universal Soil Loss Equation (USLE) as a basic tool. In 1983 Puentes proposed a methodology to determine the Land Use Capacity in relation to risk of erosion, for the soil units described in the 1:1.000.000 scale soil map of Uruguay (MAP, 1976). He followed the American scheme, and states that results are in agreement with knowledge obtained by personal experience and observations but that locally quantified data are missing to express the management - erosion relationship. During the same period, the Water Division of the Ministry developed a methodology to quantify the R value (rainfall erosivity) for the USLE (Rovira et al., 1982; Panone et al., 1983). This was followed by García in 1992, who stressed once again, the need for local research to obtain values for the C factor (land use and management) of the USLE.

The research presented here was defined within the above described context, to study the effects of soil management on physical conditions. The relative importance of several physical aspects of the soil as well as the presence of an argillic B horizon have been studied for their effects on risk of rainfall erosion.

Several steps were followed for the development of this research. Initially, three experiments and several laboratory methodologies were defined to study the effects of soil management (tillage, rotations and green manure incorporation) on soil physical properties. Chapter 2 describes the region where these experiments were conducted and ends with the presentation of our research questions. As an additional measure, other laboratory methodologies were selected to obtain more standardized values to express the relationship physical status - soil losses by rainfall erosion. These methodologies were performed at Wageningen Agricultural University. The last step of the research consisted of working with a computer simulation model. This allowed the rapid prediction of the effects of changes in the individual soil characteristics, on the soil water balance (thus on soil losses due to rainfall erosion). Chapter 3 discusses the background theory and methodologies selected to fulfil the aims of our research. Chapter 4 includes the actual description of field experiments, laboratory procedures and the computer model. Chapter 5 presents the results of every method used followed by a discussion about each method's ability to express changes in soil status. Modelling of water movement under the studied conditions is discussed in Chapter 6.

Chapter 7 proposes an assessment of soil quality, by giving ranges for those characteristics which showed a major influence on behaviour towards erosion in the sites where this project was carried out. Lastly, the conclusions in Chapter 8 critically refer to the quality of the information obtained through the several methodologies applied. It discusses the advantage of making available a fast and quantified test procedure for assessing behaviour of the soil towards risk of rainfall erosion and refers to the need for further research to make that tool more precise.

2 RESEARCH CONTEXT AND HYPOTHESES

2.1 Description of the region

2.1.1 Location

This research work was carried out in Uruguay, a South American country situated between Brazil and Argentina (Fig. 2). The latitude varies from 34 to 36 degrees South. The experiments were conducted in Paysandú, 380 km north-west from the capital, Montevideo.

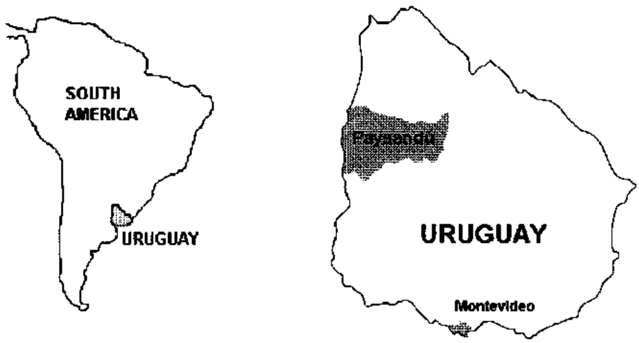


Fig. 2. Map of Uruguay and its location in South America.

2.1.2 Climate

Uruguay has a temperate climate with annual rainfall in all seasons. It is classified as Cfa according to Köppen's classification system (Köppen, 1936). The average temperature is 19°C with a relative air humidity of 65-70%. During the summer (Dec-Feb) the average temperature is 25°C and during the winter (Jun-Aug) 13°C, with frost being quite common (Universidad de la República, 1971). The average yearly precipitation is 1100 mm, which is fairly evenly distributed throughout the year. This is shown together with the distribution of the EI_{30} within a year in Fig. 3. The EI_{30} is the product of the Kinetic Energy (E) of a shower and its maximal rainfall intensity during 30 minutes. For Uruguay this was calculated taking into account the showers larger than 13 mm and more than six hours apart, considered as erosive storms by Rovira et al. (1982) and Panone et al. (1983). The R-factor of the USLE formula (Wischmeier and

Smith, 1987), is the sum of all the EI_{30} products of one year and is a good measure for the erosivity of the rainfall. For Paysandú a value of 659 was obtained, expressed in J m^{-2} mm^{-1} 10^3.

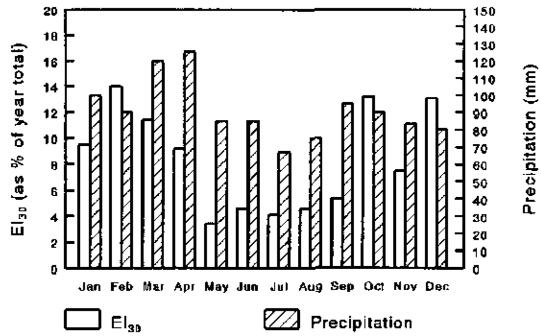


Fig. 3. EI_{30} as % of year total and precipitation per month for Paysandú (Source: Universidad de la República, 1971 and Panone et al., 1983).

The above mentioned authors show a concentration of total and erosive storms in spring and summer months. These data are presented in Table 1 for the area under study. On the average, there are 80 rainy days per year with an average amount of 15 mm per shower. One third of these showers are considered to be erosive.

Table 1

Total and erosive storms (expressed as %) occurring in Paysandú, distributed over seasons (Source: Rovira et al., 1982 and Panone et al., 1983)

Season	*Total storms (n)*	*Erosive storms (%)*
Summer	30	31
Autumn	22	21
Winter	22	17
Spring	26	31

2.1.3 Soils and topography

Major soil types in Uruguay are Phaeozems (FAO - UNESCO, 1974) of varying textures developed on sediments of the Pleistocene, deposited over several parent materials depending on the area. In Paysandú these are limestones, sandy rocks of the Tertiary Period and Basaltic lavaes. Usually these soils have an argillic B with unfavourable physical conditions which are frequently mentioned as a limiting factor for crop development, although there are no quantified data about the relative influence. Vertisols and vertic profiles are quite frequent in the basaltic area. Planosols form on sandy parent materials, having a deep sandy A horizon and a heavy clayey B horizon. Due to their characteristics the soils are rather wet in winter and dry in summer and generally nutrient rich although deficient in phosphorus. The soil map of Paysandú is shown in Fig. 4. Our experiments were placed in the shaded soil units, Young, San Manuel and Algorta (described in § 4.1). The topography of the area is undulating, with slopes ranging from 0.5 to 15%.

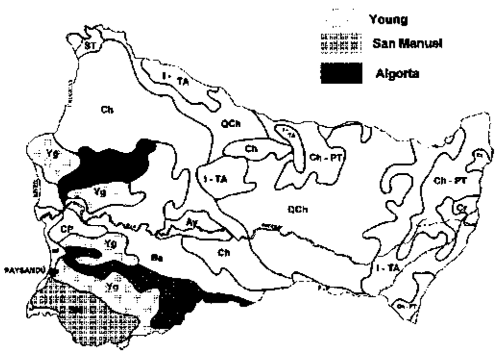


Fig. 4. Soil map of Paysandú, Uruguay. (Source: MAP, 1976)

2.1.4 Land use

Land use types are presented in Table 2, for 1981 (DICOSE, 1981), and 1990 (local information) for Paysandú. The main winter crops are wheat, oats and barley, while summer crops are sorghum, sunflower and maize. Until around 1970, continuous cropping was the most frequent cultivation system, either with a winter or a summer crop. From then onwards, the low prices of cereals introduced rotations with pastures as normal cropping systems. Variations in total area dedicated to the different crops occur due to annual price fluctuations.

Table 2
Land use types in Paysandú for 1981 (DICOSE, 1981) and for 1990 (local information)

Use	*1981*		*1990*	
	1000 ha	*%*	*1000 ha*	*%*
Planted grasslands	52.7	3.8	60.1	4.8
Natural grasslands	1159.0	84.6	1046.0	82.8
Improved grazing fields	31.7	2.4	24.9	2.0
Annual forages	23.6	1.7	27.4	2.2
Annual crops	74.1	5.4	69.8	5.5
Planted forest	22.8	1.7	25.9	2.0
Orchards and vineyards	5.4	0.4	9.4	0.7

2.1.5 Soil erosion and conservation

The situation with respect to erosion in the country for 1978 is presented in Fig. 5.

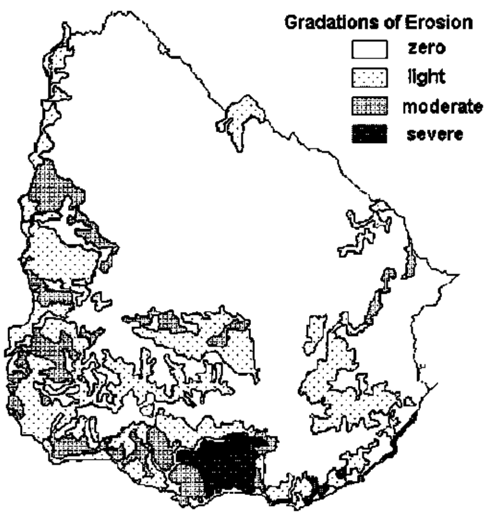


Fig. 5. *Actual erosion in Uruguay in 1978. (Source: Cayssials et al., 1978)*

There are no publications showing present conditions in Uruguay. As land use has not significantly changed on a national scale, this map can be roughly considered as showing the present situation with respect to relative degree of erosion among the different regions. In all regions there has been an increase on the area and on the severity of erosion effects. According to information presented by MGAP (1979), 30% of the country is to some degree affected by erosion. This becomes really important when referring to the total acreage of arable land available. More than 80% of these arable lands are affected. Physical degradation is reported to be found in about 20% of the country; this being more an assumption than a quantified conclusion. Historically, continuous yearly conventional tillage (performed since the beginning of this century mainly for wheat and maize), has been the reason for a decrease in organic matter levels and an increase in erosion damage that ranges from moderate to severe. Conventional tillage implies one or two times disc ploughing, followed by several passes of secondary tillage implements (mainly offset disc harrow). In severe situations, there exist other reasons for erosion besides high intensity use and steep slopes. These are socio-economic aspects, such as small size of fields (mainly around Montevideo), low prices for agricultural products that make it difficult to incorporate more expensive technology, type of tenancy that does not give permanency to farmers on the land, and often a lack of knowledge and/or inappropriate habits.

Only after 1970 some conservation practices were developed, mainly grass strips following the contour lines. However, these are almost never respected as guides for the direction of tillage practices so are rather ineffective. Aside from these, soil conservation practices are limited to small areas of narrow based temporary terraces, mainly in Paysandú. Only a few big farms which grow permanent crops such as citrus and eucalyptus are using broad based permanent terraces.

The incorporation of crop residues into the soil, mainly of sunflower is slowly being adopted during the last 2 or 3 years. This "cultivo de segunda" (planted at a time that is late for an optimal development of the crop), was primarily introduced for economic purposes (oil), while the protection of the soil in summertime is an additional advantage (covered fallow).

In recent years, some farmers have been experimenting with no tillage, as a direct result of the lower prices of herbicides compared to previous years. Still, the direct-drilling technology is not yet adjusted as to be really effective for soil conservation. The soil is left in a bare condition by use of herbicides during risky periods (from planting until the crop is covering the soil surface and can act as an effective protection against rain erosivity). Besides, barley residues are burnt since they have been reported by farmers to negatively affect the next crop.

Conservation practices and cropping systems have been changing in Uruguay due more to economic reasons than as a result of an understanding of processes going on. Some innovations, such as grass strips, have been imposed by credit institutions but refused by most of the farmers, since investments increase and no profits can be seen in the short term. This leads to a half-way situation, where the strips are installed but not utilized. Soil structure of agricultural fields is often deteriorated due to over-intensive tillage and/or grazing, and physical measures to prevent erosion (like grass strips or terraces) are not sufficient to prevent further soil degradation. Direct drilling is seen by the common farmer as a way to reduce the costs of tillage rather than as having a positive effect on physical conditions.

2.2 Research hypotheses

The influence of soil physical properties on its productivity and performance towards rainfall erosion risk has been studied for years. Nevertheless, results are diverse and sometimes contradictory. This research is based on several hypotheses that combine soil characteristics with management aspects. It is aimed at giving general answers, working within a framework where different aspects come together. In this context, the following **hypotheses** are posed.

- Tillage practices are excessive. Physical improvement and thus a reduction of soil losses, can be achieved by reduced tillage together with incorporation of crop materials. An improvement of the argillic B horizon when present, is needed to obtain a really relevant change in performance towards rainfall erosion.

Several research**questions** arise, possibly to be answered here.

- How far can tillage practices be reduced to promote an improvement on soil physical status?

- Will burial of green manures benefit the soil quality, in reference to its behaviour towards rainfall erosion?

- What is the relative importance of management (tillage intensity and green manure incorporation) and of soil characteristics (conditions for slaking, textural B horizon) on particle detachment caused by raindrop splash and on water movement through the profiles?

A final aim of this research is the development of a Soil Quality Index that expresses the ability of a certain soil to resist surface degradation and to allow water entry and water transfer through the layered profile. This index has to consider those soil characteristics that can be easily measured and that can best express changes due to management.

3 THEORETICAL FRAMEWORK

3.1 Introduction

Since our research is wide and complex, it is not practical to treat it as a whole. For better identification and understanding of the processes, the following steps have been defined:

- The first step is to study soil physical changes due to management systems (tillage, traffic, crop rotations, incorporation of green manure). Soil degradation results from intensive tillage operations without proper replenishment of lost organic matter, and is the main cause of soil loss by rainfall and of reduced crop yields. Evidence of soil degradation is analyzed through structural stability, porosity and resistance to penetration (§ 3.2).

- The second step is to quantify the effects of the physical status of the top layer on particle detachment by raindrops (risk of erosion). Sediments collected in splash cups under natural rainfall and by means of a small rainfall simulator are viewed at this point, as evidences. One of the results of degradation of physical aspects is crust development. Its relative influence to hinder water movement through the soil is also studied by using a sealing index (§ 3.3).

- The third step deals with the relative influence of the presence of an argillic B horizon on water behaviour. The pF curve is thought to show the characteristics of this horizon, making it an impediment for water infiltration and thus promoting water runoff (§ 3.4).

- The use of modelling to simulate the water balance is reviewed in § 3.5. The definition of a Soil Quality Index is studied in § 3.6 as a tool to gradate the risk of erosion, considering the best expressing characteristics.

3.2 Effects of soil management on physical properties and on crop yields

We consider a soil cultivation system (soil management) to be a sequence of cropping and tillage operations aimed at creating and maintaining good soil conditions for high production. This definition involves both short and long term concepts. On one hand (short term), the conditions that affect crop production have to be defined and knowledge of how tillage acts is needed in order to favour these conditions. With reference to the long term concepts, conditions that affect soil erosion and degradation have to be taken into account, and the mechanisms by which they are influenced by cropping and tillage systems must be well understood. Structural evolution is the determining factor for the agronomic effectiveness of seedbed preparation techniques. The germination and the emergence of seedlings are closely related to properties for the transfer of water, gas and heat and to the mechanical properties of crusts that are likely to form, thus closely related to soil structure.

3.2.1 Tillage and traffic

A description is given below of both the positive and detrimental effects of tillage as seen by several researchers. On the other hand, the effects of no tillage are analyzed, together with its possibilities of success. Traffic is studied, as it accompanies every farming system and causes negative effects on the soil. Indicators of the soil status that allow the effects of tillage, no tillage and traffic to be assessed are described in a last paragraph.

Tillage

The effects of tillage on the soil are linked with those of traffic, often acting as effects and counter-effects. Tillage tools apply forces to soil which cause changes in volume, cutting, transport, shear plane formation (crumbling, pulverisation) and changes in (micro) structure. These changes are favourable for obtaining a soil condition for enhanced agricultural production by increasing emergence, improvement of plant rooting, increasing infiltration, and controlling erosion. Schafer and Johnson (1982) present a review of expected changes due to tillage actions. They mention four types of soil failure in terms of stress-strain behaviour: compression, shear, tension and plastic flow. A tillage tool may transfer a system of forces that creates all four types of reactions. The type and extent of reactions caused by tillage determine the soil's final condition. Work done by Ojeniyi and Dexter (1979) points out the importance of number of passes and timeliness of tillage. They describe two main effects on the soil macro-structure occurring during each implement pass. The first is that the mean aggregate diameter is reduced as a result of fragmentation. The second is that the aggregates are sorted with the smaller ones tending to sink to the bottom of the tilled layer and the larger ones tending to rise to the surface. Although both effects are beneficial, the effect of multiple implement passes on soil macro-structure is not always positive. In their research, Ojeniyi and Dexter worked with a sandy soil and recorded moisture content at every pass. They reported that the first and second tillage passes produce most of the soil break-up. A second pass produces greater variation in soil structure when done at a moisture content of about 130% of the plastic limit than when done at a moisture of about 65% of the plastic limit. A summary of the effects on the soil, of the main types of tillage implements considered in our research are shown in Table 3.

Table 3

Effects on the soil of some tillage implements, used under wet or dry conditions

	Implement					
	Disc plough		*Chisel plough*		*Offset harrow*	
Effect	*wet*	*dry*	*wet*	*dry*	*wet*	*dry*
pulverising						
loosening						
mixing						
inverting						

big:	
medium:	
small:	

Tillage systems do not necessarily imply purely tillage operations. Within our research, *conventional tillage* refers to the most widely used combination of tillage implements utilized in Uruguay for almost one hundred years. It consists of several passes of a plough (either mouldboard or disc plough) followed by disc and tine harrowing. *Vertical tillage* considers the use of a chisel plough and a spring tine cultivator, with the least possible number of passes. *Reduced tillage* is a combination of both methods, which aims at using the least possible passes and selecting the implement according to the actual status of the soil. *Direct drilling or no-tillage*, is a method of planting crops that involves no seedbed preparation other than the opening of the soil for placing the seeds at the desired depth.

It is difficult to define one tillage system that maximizes the efficiency of utilization of soil nutrients, performs favourable weed control and at the same time, takes care of the conservation of natural resources. According to Boone and Kuipers (1970), it is possible that physical conditions will never become a limiting factor for certain soils under particular climatic conditions and with certain crop rotations. Under many other conditions though, the soil will be more sensitive and limits have to be defined. Other soils might exist where physical conditions will be a real bottleneck and problems have to be solved in the best possible way. In this research, we try to define the relevance of physical aspects for some soils in Uruguay, often mentioned as causing problems but not yet quantitatively analyzed.

No-tillage

Most authors agree that a no-tillage system is the best way to reduce soil erosion, but that the actual status of the soil must be regarded before adopting this practice. Van Doren and Triplett (1979) state that the use of the no-tillage system without pretreatment with some residue and tillage combination is not always likely to be successful. With no-tillage, crop residues and nutrients applied to the soil surface remain at or near the point of application. Soil structure, whether good or bad, tends to change slowly towards equilibrium, and organic matter and easily decomposed plant materials are mineralized at relatively slow rates. Decisions on when and how much to till should be based on whether or not the status needs changing and on the degree of change desired. In general, the no-tillage system tends to preserve the physical properties of the soil. Hence, in some very poor conditions, an improvement is needed before starting with it. Bandel (1983, 1984) shows that on some coastal plain soils in Maryland, generally 3 to 6 years are required for the yields of no-till corn to equal the yields of corn grown under conventional tillage. The reasons he attributes to this are that there is time required for changes in soil physical properties to develop after beginning with a no-tillage system. The recovery of the original structure of the soil (lost by continuous cultivation) is needed, by development of root channels and active fauna forming interconnected macropores, thus improving internal drainage. Although Blevins (1984) claims that the system is suitable over a wide range of soil types and slope conditions because of the soil and water conservation benefits, he poses doubts concerning the adaptability of poorly drained soils. Poor growth and emergence are related to lower soil temperatures, loss of N, disease and insect damages during a time of reduced vigour of plants due to low levels of oxygen following rainy periods. For no-tillage to be effective, a sophisticated level of field management has to be considered, adapting planting dates, plant populations and more precise and careful management of N fertilizer.

Traffic

Existing literature points field traffic as one of the most important factors adversely affecting the physical condition of the arable layer of agricultural soils which is always linked to mechanized farming. Field traffic causes compaction. Compaction causes a reduction in air filled porosity, which is important for root development. With compaction, diffusion of oxygen from the atmosphere into the soil is reduced. Loosening of the soils by ploughing usually does not completely alleviate the effects of compaction on soil structure (Arvidsson and Håkansson, 1993) and the residual effects often largely affect seedbed quality and root growth as well as the need for secondary tillage (Håkansson, 1994). The magnitude of compaction depends on such characteristics of the soil as structure, texture and hydrologic regime. Compaction acts on the solid phase, increasing cohesion among particles, and on the porous phase, decreasing it. Carrasco (1989) reported that extremely sandy and clayey soils are less susceptible to compaction, due to low cohesion and to a high tendency to self-mulching respectively, and that soils with 20% clay and 60% sand are the most susceptible to compaction due to traffic. He worked on field experiments in Sao Paulo (Brazil) generating increased compaction in soil by successive passes of machinery on a range of soil types.

In a review of soil compaction by agricultural vehicles, Soane et al. (1982) presented data on the area covered with wheel tracks and the number of passes of tractor and implement wheels under several circumstances. For one growing season of cereals or sugar beets under highly mechanized conditions, they reported at least 9 machinery passes and at least 75% of the field covered with wheel tracks. Kuipers and van de Zande (1994) report data obtained by Van de Zande (1991) for The Netherlands and Halloway and Dexter (1990) for southern Australia depending on rotation and on farm size. Table 4 presents a summary of their data, being traffic intensity expressed after Eriksson et al. (1974). In Uruguay, although they have not been measured, conditions and data would fall in between these figures.

Table 4
Annual coverage with wheel tracks and traffic intensity (after Eriksson et al., 1974) for winter wheat in The Netherlands and in southern Australia. (Source: Kuipers and van de Zande, 1994)

	Annual field coverage with wheel tracks	*Traffic intensity t km ha^{-1}*
The Netherlands		
<35 ha to 1200 ha	252%	115
Australia		
>2000 ha	165%	62.7

Methods of reduced tillage and traffic are intended to avoid high levels of compaction. Ellis et al. (1982) working in Great Britain on a silt loam series and Francis et al. (1987) on a silt loam in New Zealand, reported equivalent or sometimes higher crop yields under reduced tillage and stubble retention systems than with conventional tillage systems over a wide range of environmental conditions.

Indicators

Penetrometer resistance. Lowery and Schuler (1994), working with two profiles in Wisconsin (USA), found that compaction effects persisted for more than three years, from 16 to 46 cm in a silt loam soil, and from 18 to 34 cm in a silty clay soil. They define plant height and soil strength (measured by cone penetration resistance) as the most reliable methods of evaluating the persistence of subsoil compaction. This is in agreement with results presented by Carrasco in 1989. Mechanical resistance is highly affected by the state of compactness. When total porosity and macroporosity decrease, the soil matrix becomes more firm. The rate of elongation of root and shoot is controlled mainly by the soil strength over a range of field conditions commonly found (Barley et al., 1965). The main types of soil deformation caused by volumetric growth of roots and underground shoots are shear and tensile failure. Penetrometer resistance is related to shear strength (Tijink, 1988) and is easily measured. Many authors report in literature that there is no consistent relationship between root density and penetration resistance. It has been reported that the presence of a mechanical constraint negatively affects the development of roots but it does not always result in a lower yield. Francis et al. (1987), working on a silty loam soil in New Zealand

and Whiteley and Dexter (1982), working on a fine sandy loam in South Australia with a heavy clay B horizon, demonstrate the relative ease with which roots grow along cracks rather than through compacted soil. Although some authors such as Taylor and Gardner (1963) proved that penetration resistance is a valuable empirical tool in specific experiments, others like Ehlers et al. (1983) invalidated it for general application under different experimental conditions. This is explained by the complex system of functional relationships between soil compaction and crop growth (Boone, 1986). According to Burke et al. (1986), it is not a particular property of a soil but rather the summation effect of several properties, that can point out a problem worth to be studied further with other methods.

Bulk density and Porosity. These are indicators of compaction. Addiscott and Dexter (1994) express that, whereas mass is conserved during fragmentation by tillage, porosity is not. It has been found in soil aggregates collected from the field that porosity decreases or density increases with a decrease in aggregate size. Brown et al. (1992) found 1.21 g cm^{-3} as an optimum bulk density for plant growth and 1.47 as critical for a silty clay loam with fine montmorillonitic clay using a regression relationship developed by Jones (1983) for bulk density versus silt plus clay content. Bulk densities beyond 1.2 have been reported to significantly reduce corn yields on an alluvial clay soil (Phillips and Kirkham, 1962).

Seedbed quality. Braunack and Dexter (1989) presented a scheme to characterize seedbed quality which consisted of scoring several aggregate size ranges from 1 (undesirable) to 3 (desirable), according to their effect on some principal physical properties of seedbeds. When adding the partial scores, the obtained summation expresses the quality; the higher the better. The physical properties of seedbeds that were included in this rating were: lowest evaporation, greatest intra-aggregate aeration, greatest inter-aggregate aeration, least wind and water erosion and lowest compactability. When every physical property is given the same weight, the aggregate size range 1-2 mm turns out to be the best option. In the case where erosion is a limiting factor, the 2-4 mm aggregate size range is given a weighted factor of 2 and becomes optimal. According to the authors, this simple scheme represents an attempt to simultaneously consider the main physical factors influenced by aggregate size, such as compactability and temperature transmission.

Stability of structure. The quality of the seedbed is important but it must be accompanied by an indicator of resistance of the aggregates to external forces. To quantify the relatively fragile nature of ploughed soils, with their initially greater proportion of coarse porosity, Hamblin (1982) determined the stability of structure. Boone (1986) reported that even small changes in soil structure that occur in situations nearly critical for root growth, may have significant consequences. He stated that the definition of critical values for single factors is complicated, since many critical field situations often occur by a coincidence of several near-critical factors. Following this thought, many authors investigated stability by developing a wet sieving method and reported it to be a valuable one (Carter, 1992; Kochhann and Denardin, 1992; Thorburn, 1992; Kay et al., 1994; Rasiah and Kay, 1995). Bickerton (1988) states that the method has good reproducibility. De Boodt et al. (1961), report a high correlation between this indicator and crop yield. There are different opinions in literature about the sampling and pre-treatments to be followed in order to allow the method to better express the environmental effects on soil structure. The size, quantity and stability of aggregates reflect the resulting effect of factors which favour the aggregation of soil particles (e.g. wet-dry cycles, organic matter amendments) and others that cause their disruption (soil cultivation, bioturbation). The measurement of the stability of soil aggregates depends both on the forces that bind them together and the disruptive forces applied. The former depends on the environmental history of the soil, and the latter, on the conditions imposed during soil sampling, preparation and analysis. Several studies done by Kemper and Koch (1966); Kemper and Roseneau (1986) stress the importance of these factors and propose a standard procedure for measuring aggregate stability. Their method involves air drying and rehumidifying the samples prior to wet sieving to determine the recovery of aggregated particles on one (250 μm mesh) sieve. This procedure has been broadly applied. Several modifications have also been attempted. Elliott (1986) used gentle misting and slaking of soils prior to wet sieving as a means of contrasting differences in aggregate distributions under different management histories. Others have focused on the susceptibility of soils to disruption with chemical dispersing agents, such as periodate and sodium pyrophosphate (Tisdall and Oades, 1979), or with several degrees of physical disruption, such as ultrasonic dispersion (North, 1976), or other methods of mechanical agitation in water (Monrozier et al., 1991). These variations make the specification of the procedure critical to the interpretation of the data. The sampling method, pre-treatments, and conditions and time of storing, define the qualitative condition of the samples for the analysis.

Soil hydraulic properties. They are also indicators of the effects of tillage and traffic on the soil. The pF curve, the relationship between retention force and moisture content of the soil, depends mainly on the diameter of the pores. Macro and medium pores depend on tillage. Decreasing the bulk density, the total porosity increases and hence, the amount of water held at low soil water potentials increases while the amount held at higher potentials (larger negative values) decreases (Unger, 1975; Klute, 1982). It can also show variations depending on management since this has influence on structure. Kooistra and Boersma (1994) found that moisture content at saturation is 10% higher in pasture land than in compacted soils. Volumetric water content was found to be consistently higher in soils maintained under conservation tillage systems than under conventional tillage systems (Pidgeon and Soane, 1977; Lindstrom et al., 1984). The saturated hydraulic conductivity is mainly governed by the large pores and lowered by compaction. Many investigators report increased saturated hydraulic conductivity under no-tillage systems and explain it by the presence of continuous macropores enhanced by root and fauna development (Chan and Mead, 1989; Wu et al., 1992). Other reports in agreement with those already mentioned are presented in a review by Unger and Cassel (1991).

3.2.2 Crop rotations and green manure incorporation

Whereas tillage operations are used, among other reasons, to create a range of transmission pores in surface soils, the stability of aggregates is largely dependent on the organic material added. An increase in organic matter levels and enhanced biological activity are both characteristic of the changes which occur in the soil under a pasture. For this reason, management of the soil to develop optimum physical conditions for arable crop production is unlikely to be achieved by tillage alone and requires that the soil be managed in such a way that internal aggregate conditions are maintained in a fashion similar to those developed under pasture (Greenland, 1981).

Torres (1994) working in Uruguay refers to the advantages of avoiding a long, bare fallow to prevent nutrient losses, weed development and erosion, in order to efficiently carry out tillage aiming at soil conservation. He stresses the need for introducing cover crops and green manure incorporation, together with reduced tillage practices. Plants or plant residues influence soil biological activity by providing protection and a food source. Chisci and Boschi (1988) working in Italy with a Vertic Eutrochrept (51% clay at the surface layer), show with respect to protection against water erosion in hilly areas, that it is more beneficial to include a perennial forage crop in the rotation (alfalfa in this case) than to change the tillage practices from up and down the hill to contour ploughing. Benefits from surface mulching to avoid tillage have been reported by several authors such as Lal (1975) and Gupta and Gupta (1986). Crop and vegetation residues protect against raindrop impact, reduce the rate of runoff, modify soil temperature and drying, and provide a food source for soil fauna. Incorporation of organic amendments either as farmyard manure or as green materials (crops being buried at a certain stage of their growing period) has also been shown to improve yield and soil physical properties (Biswas et al., 1964; Charreau and Fauck, 1970). Macropores are important for water entry, and it is important to promote the development of a macropore network through soil horizons associated with poor physical properties. The biological approach is meant to achieve enhancement of physical properties and is successfully being used in the humid tropics. More research is needed under other growing conditions, on biologically-based and ecologically sustainable systems to improve structure by means of biological processes. In Uruguay, field descriptions always report meso fauna as almost non-existent in the argillic B horizons and root densities as low. For these reasons, we tend to agree that conditions in winter are very difficult for biological activity, due to high moisture content that, together with the swelling characteristics of this layer, result in low levels of oxygen.

A combination of tillage systems and residue handling is desirable to achieve optimum soil structure status. In Brazil, Kochhann and Denardin (1992) consider that green manures are necessary to be able to start with direct drilling. They mention specific crops such as oats, serradela, rye and others, which are sown and cut at flowering with residues left on top. Doran (1980) showed the effects that mulching has on increasing microbial populations, through the increase of soil water near the surface and the addition of organic matter and nutrients. Working in Nebraska on a silty clay loam (montmorillonitic) soil, he reported an increase in the number of micro organisms and also in their metabolic activity. Carter (1992), working on three fine sandy loam profiles, confirmed that minimum tillage systems for cereal cropping have the ability to improve soil structure stability under humid conditions. In the case of low resistance to compaction and limited potential for regenerating adequate macroporosity, it is necessary to combine improved tillage methods with systems which reduce excessive soil compaction (controlled traffic) along with an incorporation of green manure, to obtain positive effects on structural stability.

3.3 Effects of soil management on the surface layer

3.3.1 Infiltration

Surface infiltration depends greatly on textural and structural characteristics of the top layer. Values of terminal infiltration rates for vertisols in ICRISAT, India, reported by Klaij (1983), are among the lowest reported in literature. They average 5 mm day^{-1} in soils with 50 to 64% montmorillonitic clay. Water surface infiltration and temporary surface storage are processes directly influenced by tillage systems and residue cover. Mouldboard and disc ploughing are usually reported as leaving a greater surface roughness immediately after tillage when compared to chisel ploughing and no-tillage, thus enhancing the infiltration rate. When considering residue covers left by the different tillage systems, the tendency is just the opposite. When a balance is made between both characteristics, Van Doren and Triplett (1979) report that in several soils being tested in Nigeria and Ohio, rains of up to 20 mm should be equally conserved by all systems. However, greater rainfall would cause a greater runoff under mouldboard ploughing, while no-tillage would have an increasingly superior infiltration capacity due to its ability to maintain actual conditions. In Brazil, Kochhann and Denardin (1992), found infiltration values decreasing from 136 to 0.2 mm h^{-1} for native forest and after 20 years of mechanical tillage respectively.

Residues on top are regarded as relevant even under no-tillage systems. Stobbe (1994) reports that with bare soil, infiltration is higher under ploughed soil than under no-tillage, but is opposite when residues are on top. Derpsch et al. (1986) found the same tendency working in several soils in Paraná, Brazil. Their data show the highest values under no-tillage, intermediate under chisel ploughing and the lowest under conventional tillage. They conclude that the infiltration rate decreased in proportion to the decrease of soil cover. Kemper and Derpsch (1980/1981) working with Oxisols and Alfisols in the north of Paraná, Brazil, present data showing a consistent increase in infiltration rates when cover crops are used. Thorburn (1992) concludes that both tillage system and stubble retention play a role in modifying roughness and hence infiltration.

3.3.2 Splash and runoff

The term soil loss, expressed as a quantity per unit area and time, is often used in literature for small plots. But even in the most erodible situations, soil loss or sediment yield is limited by the transport capacity of the runoff. According to Mutchler et al. (1988), as runoff flows through a watershed, the occurring changes in topography, vegetation and soil characteristics, often reduce the transport capacity. Gross erosion in a watershed, as predicted from plot results, must be reduced by a sediment delivery ratio (unique to each watershed) to obtain the expected sediment yield. They describe small plots as tightly controllable, allowing for studies of isolated variables, but cannot consider the large spatial variability of soil and rainfall. Rainfall simulators are used in small plots to measure splash and runoff. Different sizes of plots and rainfall simulators are referred to in literature. Kamphorst (1987) developed a rainfall simulator to work in plots of 0.06 m^2. Meyer (1988) describes conservation research based on big rainfall simulators. Mutchler et al. (1988) describe research done in big plots (around 2 hectares) with appropriate equipment to collect runoff and sediment.

Raindrop impact, through its ability to detach soil particles, along with weathering, comprise the first stage in the soil erosion process. This force has to overcome the particle weight and the cohesive force which binds the particles together. Quansah (1981) states that the interaction between soil and rainfall intensity is the most influential in particle detachment (splash) while the interaction between slope and rainfall intensity influences sediment transport (runoff). Ellison (1944) reported that the results of raindrop erosion are most apparent at the tops of hills where return splash does not balance outgoing splash. He states that most of the severe sheet erosion found at these locations is largely caused by raindrop splash, while erosion by surface flow is usually more apparent near the base of slopes where the greatest amount of surface flow concentrates.

Kochhann and Denardin (1992), working with soils in Brazil, report that the simple decision of keeping residues on top, even under conventional tillage, causes a reduction in losses of 70%. Derpsch et al. (1986), working in several soils in Paraná, Brazil, demonstrate that with no soil cover, total infiltration was between 20 and 30% of the rain applied, while with 100% cover, infiltration was 100%.

3.3.3 Crusts

Crusts (final dry form of seals) are formed by raindrop impact causing the breakdown of soil aggregates. The smaller detached particles are dispersed and settle down filling and blocking the larger pores of the soil surface. A process of compaction of a thin surface layer occurs under the impact of raindrops, bringing this layer to a higher density and lower porosity, that adversely affects water infiltration. Zuzel et al. (1990) working on a silt loam in the Pacific northwest of the United States, claim that surface sealing is more important than a tillage pan in reducing intake rates and in increasing runoff and soil erosion. Hoogmoed (1994), differentiates between crusting and sealing, a seal being a very thin and low strength layer when dry, having no impact on seedling emergence, but reducing the movement of water through the surface. Seal formation can occur even in sandy soils, where values of final infiltration rates decrease in one rain storm 10 times with respect to the initial value (Hoogmoed and Stroosnijder, 1984). Losses of 50-90% of the volume of rain showers can occur in those cases, which severely influence water balance. As a side effect on heavier soils, once the seal turns into a dry crust it can become a barrier for the emerging seeds. In sensitive crops like grain sorghum, soybean and others, this can cause delayed or partial emergence (Awadhwal and Thierstein, 1985).

The susceptibility of the aggregates to rainfall induced surface sealing depends on a combination of soil physical, chemical and biological processes highly affected by climatic and soil conditions during seal formation (Bradford and Huang, 1992). Römkens et al. (1985) report the seal hydraulic conductance to decrease in an exponential manner with the cumulative rainfall energy. Eppink (1992) states that aggregates held together as long as the strength of the forces combining the particles within them exceeds the external forces applied from the environment in which they exist. Texture is reported as relevant with respect to crust formation. High silt content favours crusting and crust strength, while a seal on soils with high clay content restricts the final infiltration rate to a greater extent (Shainberg, 1992). Smectite clays are more dispersive and therefore, more susceptible to sealing than kaolinitic clays (Frenkel et al., 1978). Organic matter is reported as playing a vital role in aggregate stabilizing since it acts as a binding agent between particles (Emerson, 1959). Cogle et al. (1994) refer to soil biota as having an important role in improving the surface structure, mainly of hardsetting, crusting and sealing soils, by increasing the ability of the soil to conduct water through the surface soil layer and decreasing runoff losses.

3.4 Effects of an argillic B horizon on water movement

In Hillel (1980), five factors are given on which soil infiltrability depends; one of them is the presence of impeding layers inside the profile. Layers which differ in texture or structure from the overlying soil may restrict infiltration, either because of a lower saturated conductivity (as is the case with clayey layers) or because of a lower unsaturated conductivity (like sand layers). A main physical characteristic of an argillic B horizon is a very low saturated hydraulic conductivity. In literature, values lower than 5 cm day^{-1} are considered to lead to stagnant water and perched water tables based on an average shower intensity of 2 mm h^{-1} (Kooistra and Boersma, 1994). An extreme case of argillic B is presented by Rooyani (1985) for Aqualfs in Lesotho. The A and B in these profiles are separated by an abrupt, smooth boundary, where gully erosion starts due to the "pipes" being formed at that boundary during rainfall.

3.4.1 Continuity between A and B

The absence of pore continuity at the bottom of the plough layer is regarded as negatively affecting the water intake by the soil (Goss et al., 1984). By ploughing, the conductivity of this layer is reduced by one-third when compared to direct drilling, and the effects are greatest on clayey soils because of their lower conductivity. Ploughing causes a disruption of pore continuity at the base of the Ap horizon which can result from one single ploughing. Goss et al. (1984) mention the effectivity of a mole drainage system to increase the saturated hydraulic conductivity in the subsoil layer. This, combined with the use of a shallow-working tined implement for arable cultivation instead of a mouldboard plough results in a less rapid decline in the continuity of macropores between topsoil and subsoil, thus allowing more rainwater to enter the subsoil.

3.4.2 Influence of management

Tillage is generally performed at a depth of about 15 to 20 cm, thus in some cases reaching a B horizon that is then affected by compressive forces causing compaction. Most of the research done though refers to the arable layer. Almost no reference is found with respect to the effects of organic additions or deep rooting crops on the status of the B horizon. Felton and Ali in 1992 worked on a laboratory experiment with samples from B argillic horizons in Kentucky. Mixtures of soil with increasing amounts of organic matter (horse manure) were brought to a certain moisture content and then compacted by the Proctor compaction procedure. They found that bulk density was reduced by up to 25% after the addition of organic matter, and saturated hydraulic conductivity increased as much as 1400%. We are not considering subsoiling in this research because it is not thought to be successful due to the characteristics of the B horizons.

3.5 Modelling water behaviour

Computer assisted simulation is introduced in our research as a means of predicting water behaviour under varying soil conditions. Models of water balance are built in order to show how a certain amount of rainfall distributes over four components: a) infiltration and distribution in the different soil layers, b) drainage to deeper layers, c) evapotranspiration and d) losses as runoff. According to Stroosnijder (1982), there are several reasons that make simulation complex. Among these, the fact that the relationship of the soil water potential to the water content of the soil is quite non-linear, that conductivity for water depends on the water content, and that the water content of each soil layer cannot be considered a separate state variable.

While empirical models involve either approximations of the physics involved, or no physics at all, mechanistic models attempt to employ the best physics available and deal with the processes as are currently understood (Bristow et al., 1994). Since mechanistic models incorporate the essential mechanisms, it is possible to use approximations of the system properties and still obtain valuable information about system response under a range of different conditions. Also, these models usually have good predictive capability, at least in a qualitative sense, because of the way they are built up and can be used to extrapolate results of studies in space and time.

In literature, many different objectives are mentioned for working with computer models that describe water movement in soils. The selection of a model requires that the objectives be specified, whether predictive or explanatory. The scale of operation is also important. This can vary from a large drainage basin, to the point of impact of a single raindrop. There are models like USLE (Universal Soil Loss Equation) and CREAMS (Chemicals, Runoff and Erosion from Agricultural Management System), that estimate erosion and/or sediment yield on field-sized areas to select best management practices for the control of erosion (Knisel, 1980). ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) being a more comprehensive model, that uses modifications of the USLE (Beasley et al., 1980), also falls within this group. In some cases, the soil water balance is used in combination with a model for crop production. Feddes (1982) describes this kind of use for the SWATR (Soil Water Transpiration model) and the CROPR (Crop Production model). In some other cases, only a part of the water balance process is studied for specific purposes, as a prediction of infiltration into cracked clay soils (Hoogmoed and Bouma, 1980).

The success of the model must be judged by how well it meets the objectives or requirements. This accuracy is usually tested by comparing predicted with measured values and assessing the closeness of fit by correlation coefficients or by an error statistic. A simpler assessment of goodness of fit is to calculate the ratio of the predicted to observed value and see if it lies within a range predetermined as acceptable. For some purposes, such as comparing the effectiveness of different conservation strategies, it may be enough for the models to predict realistic percentage differences in erosion between the strategies without giving absolute values (Morgan, 1986).

Required parameters for water movement models are hydraulic characteristics of the soil. Earlier in this chapter, a review is presented about the influences of management on those hydraulic parameters, as infiltration rate, pF or water retention curve, and hydraulic conductivity. Different management systems cause a range of changes in structure, by affecting pore continuity, structural stability, crust development, thus affecting the hydraulic parameters and altering the behaviour of the soil towards rainfall. The use of a mechanistic type of model, using a mathematical equation to express the occurring processes, allows a fast prediction of behaviour when the inputs are varied. How good a prediction this is, depends on how well the equations can imitate the relevant processes as they occur in the real system (Brockington, 1979).

The model SWIM (model for Soil Water Infiltration and Movement; Ross, 1990a) applies a numerical solution of Richards' equation; a combination between Darcy's law for one-dimensional flow of liquid water in soil and the equation of continuity for a fluid of constant density. In Ross (1990 b), the theory behind this equation is described. It is the commonly accepted basis for detailed studies of soil water movement, but only lately, computation facilities have made it possible to use it. Approximations were used in earlier attempts, like the Green-Ampt approach. The principal assumptions of this approach are that there exists a distinct and precisely definable wetting front and that the matric suction at this wetting front remains effectively constant, regardless of time and position. It also assumes that behind the wetting front, the soil is uniformly wet and of constant conductivity (Hillel, 1982). Along the lines of the aims of the work described in this report, the objective of using the SWIM is to simulate water infiltration and movement in layered soils.

3.6 Soil structure quality index to assess risk of erosion

In the last few years, the interest in defining soil quality has been stimulated by an awareness that soil is a critical component of the environment. Doran and Parkin (1994) define soil quality as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health. In this context, the definition of a soil quality index involves wide interdisciplinary work. One of the components of such an index must provide an evaluation of soil with regard to sustainable production, thus resistance to erosion. Stability of structure might be regarded as such a component. Aggregates are high bulk density soil units containing small pores that enhance water retention and are surrounded by large pores. When compactive forces are applied to a layer of aggregates, a loss of large pores occurs, and aggregates break down when those forces are sufficiently large. Cruse and Gupta (1991) state that when this happens, small pores dominate, resulting in lowered water infiltration, lowered water drainage, reduced aeration and increased resistance to plant root growth. A decrease in air permeability is also mentioned, as well as a flattening of the sigmoidal shape of the water retention curve, indicating dominance of smaller size pores. Erosion rate depends on the resistance of the aggregates to breakdown. Although prediction of conditions under which compaction will occur is recognised as being difficult because they vary with time and location, it is known that if soil aggregate breakdown occurs during load application, soil physical problems are likely to follow. Therefore, the fundamentals of identifying soil conditions and applied loads that minimize excessive compaction are based on understanding the stability limits of soil aggregates at various applied loads and water contents. Luk (1979) found the percentage of wet stable aggregates greater than 0.5 mm to be the most significant soil property to explain soil loss. Nevertheless, there is conflicting evidence in literature as to how the stability is affected by other soil characteristics and its consideration as a quality indicator.

Karlen and Stott (1994) state that aggregation, surface sealing and porosity are three indicators of soil structure that can have major impacts on the critical functions associated with soil quality with regard to soil erosion by water. They demonstrate a procedure to get an index by using several soil characteristics (indicators) that are weighted according to the relative influence they have on soil quality functions, which determine the erodibility of a certain soil. The procedure although simple, needs many well quantified characteristics in order to be of general use, and in many cases, these are not available.

Other attempts to define quality can be found in literature (Canarache, 1978), also making use of several characteristics which are weighted rather subjectively, or by using common knowledge or ranges of data from literature. By these means, it is not possible to overcome all the contradictory information about the influence of certain soil characteristics on the overall losses by rainfall erosion.

A logical part in our research therefore, is to propose an assessment of soil quality with respect to resistance to erosion. The parameters to be used in this assessment are quantifiable physical characteristics, emerging from our research as the best indicators.

4 MATERIALS AND METHODS

4.1 Overview of the research

To be able to answer the questions posed in Chapter 2, we conducted three experiments as part of our research. The first, a tillage-rotation experiment, started in 1987 at the University Experimental Station located 7 km South from Paysandú. It was defined by researchers from the Faculty of Agriculture with their main objective being the evaluation of the effects of different crop/pasture rotations and tillage systems on the productivity of the soil. The hypothesis under study was that grain production could be increased by means of a more efficient use of resources (mainly nitrogen) maintaining or even improving the productivity of the soil. Within this framework, the hypotheses defined specifically for this research were tested.

After four years (1991), the experiment was no longer continued. While the measurements showing the relationship between management and physical status had been done, the relationship between physical status and soil losses still needed to be studied. A second experiment (summer green manuring experiment) was then designed that would enable the study of the short term effects of the incorporation of crops as green manures on soil physical properties and of those properties on soil losses by simulated rainfall. This experiment included the burying of summer growing crops as green manures and was carried out in a farmer's field in the 1992/93 summer period. During the following autumn (1993), our third experiment was set up also in a farmer's field. In this case, several winter crops were sown to be incorporated as green manures (winter green manuring experiment). Within the physical status - soil losses relationship, it allowed for the specific study of the risk of crust formation by means of simulated rainfall.

The region where the three experiments were performed is representative for a major part of agricultural production areas in the country. The most common rotation in the region is one of 3 to 4 years of winter crops (wheat, barley), alternated sometimes with summer crops (maize or sorghum), followed by a 3 to 4 year pasture consisting of a mixture of legumes and gramineae sown together with the last winter crop. Once this pasture loses productivity because of negative effects of direct grazing and competition by native species, the cycle starts again.

Most soils in this area are developed on silty clay sediments that date from the Quaternary period. This is the case with the soils where the tillage-rotation experiment (site 1) and the winter green manuring experiment (site 3) were performed. Site 1 corresponds to unit San Manuel and site 3 to unit Young in Fig. 4. They are classified as Luvic Phaeozems (FAO-Unesco, 1974). Clay content is high, thus the workable range is quite narrow (hard when dry and sticky when wet). This is aggravated when the B horizon is found near the surface in places where the A horizon is partially lost by erosion. The soil where the summer green manuring experiment (site 2) took place consists of a sandy A horizon overlaying a heavy clayey B one, developed on a sandy parent material from the Tertiary period (unit Algorta in Fig. 4), and classified as Mollic Planosol (FAO-Unesco, 1974). Analytical results are shown in Table 5 for the three sites.

Table 5

Particle size distribution (clay: <2 μm, silt: 2-50 μm, sand: >50 μm), organic matter and pH for the three sites under study, for A and B horizons

		Clay	*Silt* $g\ (100\ g)^{-1}$	*Sand*	*OM* $g\ (100\ g)^{-1}$	*pH* (H_2O)
Site 1	*A*	27	45	28	3.5	5.9
	B	53	30	17	1.7	6.4
Site 2	*A*	12	15	73	1.5	5.5
	B	30	12	58	0.1	7.0
Site 3	*A*	30	35	35	5.5	6.0
	B	40	30	30	2.5	6.5

In general in the region, physical deterioration and erosion are caused by continuous tillage and direct grazing. The workability deteriorates and surface sealing occurs, crop establishment and growth are hampered and yields decrease. The distribution of rainfall over the year (Fig. 3), causes an excess of water in periods where tillage is done (autumn and spring), thus making conditions even more difficult.

The last step of the research was performed in laboratories of the Wageningen Agricultural University. Specific methods were performed in order to allow for a better interpretation of the field data. The change in structural conditions was obtained in this case by compacting prepared samples under various moisture contents and the effect of simulated rainfall was then studied. Some of the data obtained were used as input data in a computer simulation model to allow for more general conclusions.

4.1.1 Tillage-rotation experiment - Site 1

The tillage-rotation experiment (1987-1991) consisted of 17 rotation/tillage treatments with three repetitions. Each treatment was split into four nitrogen fertilization levels (0, 40, 80 and 120 kg ha^{-1} of N). The experimental design consisted of completely randomized blocks with nested factors (fertilization). Our determinations were done in the sub plot fertilized with 40 units of N; thereby considering crossed factors. Main plot size was 20 m length and 10 m width; subplots were 5 and 10. The scheme is presented in Table 6. In Appendix I, the lay out of the experiment is presented as it was in the field, together with the profile description, chemical characterization and textural analysis of the different horizons.

Description of treatments

The experiment included four tillage systems and four rotation systems (different cover crops alternated with wheat), thus a total of 16 treatments. One other (control) was permanent pasture, i.e. sown with fescue at the beginning and kept as a reference, without other disturbances for the time the experimented lasted.

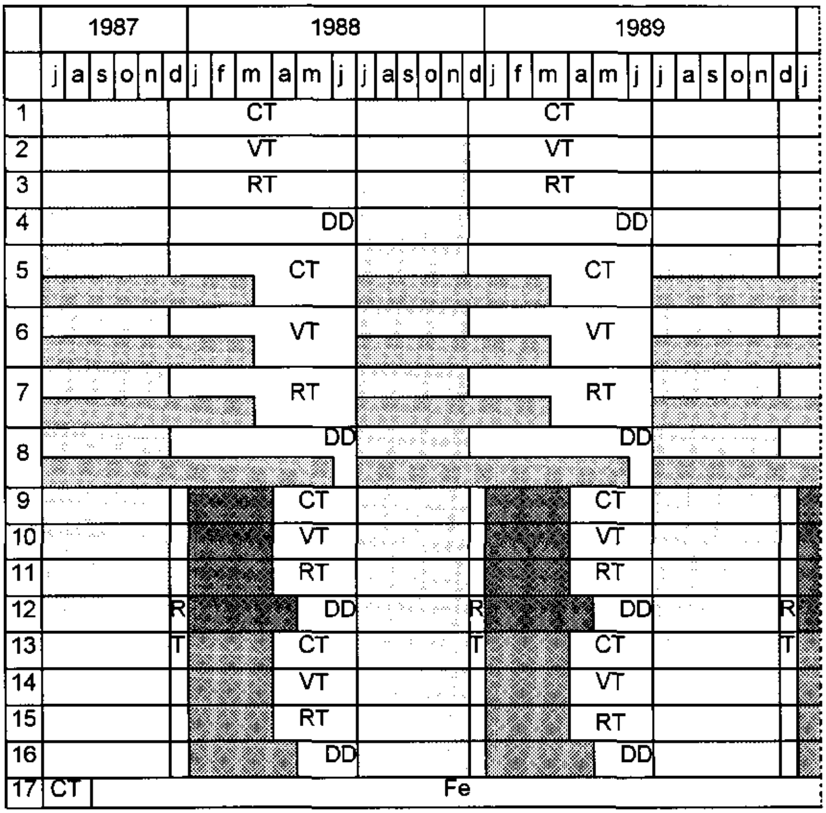
Conventional tillage (CT) consisted of ploughing with a disc plough with six discs, 1.70 m total working width with a working speed of about 6 km h^{-1}. It was set to till at a depth of 18 to 20 cm.

Vertical tillage (VT) was performed with a chisel plough with 10 spring loaded tines separated 30 cm (2 rows), with a total working width of 2.50 m and a speed of 6 km h^{-1}. The working depth was set the same as for the disc plough.

Reduced tillage (RT) consisted of a first operation with an offset disc harrow, 2.20 m working width and 8 km h^{-1} working speed. Before planting, a herbicide was used (Paraquat) in the dosage required to desiccate all the green material on the surface. Once the weeds dried out, a disc offset harrow was used again to incorporate them.

Table 6

Scheme for treatments and dates in the tillage-rotation experiment



Key to symbols

	Triticum aestivum (wheat)	CT	*conventional tillage*
	Tripholium pratense (red clover)	VT	*vertical tillage*
	Setaria italica (moha)	RT	*reduced tillage*
	Helianthus annuus (sunflower)	DD	*direct drilling*
Fe	*Festuca sp* (fescue)		

Direct drilling (DD) was performed with a regular 3m wide drilling machine, instead of with a machine with specially designed furrow-openers. The treatment only considered the use of herbicides, mainly glyphosate before sowing, and later some others specifically for the weeds that developed once the crop was established. For the rotations including sunflower and moha, some reduced tillage had to be performed before sowing the summer cover crops, based on the belief that soil conditions were very poor for a successful crop emergence and stressed by the low moisture contents of the top soils in summer time. Only the winter crop was sown without any tillage operation.

The standard tractors used for the different implements, averaged 4 tons of weight, with the rear wheels covering about 60 cm in width. There was no control of tracks, so it is assumed that compaction randomly affected the whole plot. Secondary tillage was done with the offset disc harrow (conventional and reduced tillage systems) and with the spring tine cultivator (vertical). Preparation of the seedbed was performed with a spring tine cultivator followed by a teeth harrow. Velocity for these implements was about 10 km h^{-1}.

With respect to cover crops, red clover, sunflower and moha were tested. Red clover is a legume, thus able to provide N by fixation. It was sown together with the wheat at a sowing density of 6 kg ha^{-1}, and it remained on the field after the latter was harvested. Sunflower (with a sowing density of 10 kg ha^{-1}) was tested because it provides a big amount of dry matter and is a cheap option. Moha (20-25 kg ha^{-1}) is a gramineae having a very fast growing cycle, thus being appreciated as a cover crop since it also yields a considerable amount of biomass.

Measurements and observations

Most of the equipment needed for field sampling and laboratory determinations was made available during the course of the research work. The decision about methodologies to be used was taken considering resource availability, that led to the use of non-sophisticated equipment. Field data were collected from 1991 to 1993. The following determinations were carried out during that period (for details see § 4.2).

In 1991:

- Determination of seedbed quality, by means of dry aggregate sieving. Collection of splash. Both were made in August, just after sowing of the winter crop, which was barley (*Hordeum vulgare*), as it was already late for wheat.
- Determination of bulk density one week before the harvest of the barley. This was done in three layers. The 3 to 8 cm depth layer that corresponds

to the A horizon (arable layer); the 13 to 18 cm depth layer, located at the base of the plough layer where an A_{12} horizon is described; and the 23 to 28 cm depth layer, always the B horizon. Particle density was also measured for the three depths, as well as structural instability by the Henin method.

- Measurement of height of barley plants at full development.
- Data on crop behaviour of previous years were collected.

In 1992:

- Determination of aggregate stability by means of wet sieving in the laboratory. This was done on samples taken from the seedbed in 1991.
- The rate of water infiltration was measured in the field.
- The pF curve was determined with samples taken from the B horizon. This was done after the preparation of the seedbed. The experiment was then stopped.

In 1993:

- Resistance to penetration until 80 cm depth was measured in the field.

4.1.2 Summer green manuring experiment - Site 2

The summer green manuring experiment (1992-1993) consisted of 24 treatments (23 different crops and one plot left bare fallow, as a reference) with three repetitions. The statistical design was of completely randomized blocks. Plots were of 2.25 m length and 1.20 m width. Of the 23 crops tried out as green manures, only the 8 that showed better growth behaviour were chosen to be tested for their effects on the soil. The scheme is presented in Table 7. In Appendix II the lay out of the experiment is shown together with the soil profile characterization.

Description of treatments

Tillage was done uniformly. Primary tillage was performed with a disc plough followed twice by an offset disc harrow. The seedbed preparation was made with hand implements (hand hoeing). The different crops to be used as green manures were sown in early January 1993 and were cut during the following April and the residues incorporated into the soil to an average depth of 15 cm by means of a spade. The selection of crops to be tested was done considering previous experience available from Brazil. Legumes were chosen for their deep rooting system and their ability for N fixation, together with their high biomass production. Gramineae and sunflower were selected for their high biomass production and because they were already in common use in Uruguay. More information about the crops can be found in Calegari et al. (1992). In July 1993 every plot was sown with barley (*Hordeum vulgare*).

Table 7

Scheme for treatments in the summer green manuring experiment
(Key to symbols: L: Leguminosae; G: Gramineae; C: Compositae; a,b: two varieties)

Treat.	*Latin name*		*English name*	*Uruguayan name*
1	*Canavalia ensiformis*	(L)	Jack bean	Frijol de cerdo
2	Bare fallow plot			
3	*Setaria italica*	(G)	Foxtail millet	Moha
4	*Sorghum bicolor*	(G)	Sorghum	Sorgo forrajero
5	*Vigna ungüiculata (a)*	(L)	Cowpea	Caupí maní (var)
6	*Cajanus cajan*	(L)	Pigeon pea	Guandú
7	*Crotalaria juncea*	(L)	Crotalaria	Crotalaria juncea
8	*Helianthus annuus*	(C)	Sunflower	Girasol
9	*Vigna ungüiculata (b)*	(L)	Cowpea	Caupí moro (var)

Measurements and observations

In the field:

- The amounts of green and dry biomass incorporated were recorded to be related to physical status.
- Resistance to penetration was measured in May, up to 70 cm depth.
- The rate of infiltration - runoff under a simulated rainfall on small plots was measured in June 1993.
- The amount of splash due to a natural rainfall event was measured in July, after sowing the barley.

In the laboratory:

- Measurements of bulk density, particle density and total porosity were done for three layers as follows, 0 to 15 and 15 to 20 cm depth (they correspond to two layers within the A horizon), and for the B horizon.
- Saturated hydraulic conductivity was measured also for three layers.The first from 2 to 7 cm depth, the second from 15 to 20 and the third corresponding to the B horizon.

- Determination of microbial respiratory activity was done for two layers (0 to 15 and 20 to 40 cm depth).
- Measurement of aggregate stability by wet sieving was done for the seedbed layer.

4.1.3 Winter green manuring experiment - Site 3

The winter green manuring experiment (1993) consisted of 16 treatments, 15 winter crops to be buried and one reference plot (bare fallow), with three repetitions as a completely randomized block design. The size of the plots was 5 m length and 2 m width. Only five of the crops were studied further for their influence on soil physical condition. The reason for that was a high weed infestation in the other plots that could not be controlled and thus a very low performance of the desired crops. The scheme for the experiment is presented in Table 8. The lay out, as well as the analytical data of the soil profile is presented in Appendix III.

Description of treatments

Tillage was performed the same way as for the summer green manuring experiment. The sowing was done in June 1993 and the incorporation of the crops in October. The selection of these crops was done considering previous experience in Brazil as well as in site 2. Complete information about their characteristics and behaviour is given by Calegari et al. (1992) and by Derpsch and Calegari (1992).

Table 8

Scheme for treatments in the winter green manuring experiment
(Key to symbols: L: Leguminosae; G: Gramineae; C: Cariophyllaceae)

Treat.	*Latin name*		*English name*	*Uruguayan name*
1	Bare fallow plot			
2	*Secale cereale*	(G)	Rye	Centeno
3	*Medicago sativa*	(L)	Alfalfa (lucerne)	Alfalfa
4	*Spergula arvensis*	(C)	Corn spurrey	Espérgula
5	*Avena strigosa* Schieb	(G)	Oats	Avena negra
6	*Ornithopus sativus*	(L)	Common serradella	Serradela

Measurements and observations

In the field:

- The percentage of surface covered by the crop and the amounts of green and dry biomass incorporated were recorded.
- Infiltration and runoff generated by simulated rainfall.

In the laboratory:

- Bulk density and aggregate stability.
- Ratio of saturated hydraulic conductivity before and after the simulation of a rainfall on aggregates collected from the field to study the susceptibility for sealing.

4.2 Field and laboratory methodologies

4.2.1 Assessment of seedbed quality

The dry aggregate size distribution describes a certain condition of the seedbed, expressed as a degree of crumbling. When disintegrating forces like rain and/or tillage and traffic act on aggregates, the degree of crumbling will vary depending on the aggregate strength. This methodology was chosen to study the effects of different tillage intensities on the conditions of the seedbed. It was performed by sieving and weighing the different size fractions taken from the loose seedbed immediately after seedbed preparation and sowing. The loose seedbed sample was collected from the full area inside an iron frame of 2500 cm², taken to the laboratory and allowed to air dry trying carefully to avoid further breaking of aggregates. A nest of sieves with openings of 37, 25, 19, 12.5, 9.5 and 5 mm was used. The mean weight diameter (MWD in mm) was calculated as the sum of the products of the mean diameter of each size fraction ($\overline{x}_i$ in mm) and the proportion of the total sample weight (w_i) occurring in the corresponding size fraction, as expressed in the following formula.

$$MWD = \sum_{i=1}^{7} (\overline{x_i} * w_i)$$

4.2.2 Assessment of aggregate stability

Many different ways of assessing stability of soil aggregates have been described in literature. Dexter and Kroesbergen (1985) state that the tensile strength is probably the most useful measure of strength of individual soil aggregates. They prepared aggregates to known matric water potentials by drying them from saturation and then found the crushing forces that individual aggregates required. Other authors refer to methods of assessing structure stability which involve the use of water. Water may have a disintegratory effect on soil aggregates, depending on the way it is brought in contact with the soil. The natural decay of soil aggregates can occur by hydration, swelling and shrinking of clay and by water drop impact. If the disintegratory effect of rainfall water on aggregates has to be determined, then methodologies using artificial raindrop impacts are used, as described by Dexter et al. (1984). A single layer of aggregates with diameters between 4.5 and 4.8 mm, pre-moistened on tension tables at a suction corresponding to -7.8 kPa, is placed on top of a metal plate with circular holes of 4 mm diameter. Drops of constant volume and energy fall on the aggregates causing disruption. The number of aggregates that remain on the plate after regular periods of time is recorded and is considered to express the aggregate stability. Other methodologies involve a combination of a simulated single drop rainfall and sieving under water (De Boodt et al., 1961).

Wet sieving method

To determine structural stability in our research, a method was chosen whereby the disintegration of aggregates is caused by sieving them under water. The wet sieving method described by Yoder (1936) and Kemper and Rosenau (1986), was selected and modified according to the aim of this research. The disruptive effect of rainfall is measured separately (§ 4.2.5 and 4.2.6).

There are no generalized standards for comparison of structural stability of aggregates. According to Tisdall and Oades (1982), aggregates smaller than 0.25 mm in diameter are held together by organo-mineral complexes and polysaccharides. This makes the binding relatively permanent and not influenced by organic matter content changes related to tillage. Larger aggregates (>0.25 mm diameter) are held together by roots and hyphae.

Stability of these aggregates declines when roots die and are not replaced. We decided to work on the large aggregate range since we were interested in measuring short-term effects of various management systems. Having described the theoretical background and in view of the wide variations in the experimental set up reported in literature, the nest of available sieves and the range of aggregates to work with were selected, taking into consideration that the results might be able to express relative influence of several management treatments on a certain soil. For this research, the wet sieving under water was done during 15 minutes for each sample. The sample consisted of 30 g of air-dried aggregates 4.5 to 9.5 mm diameter obtained from the material taken from the seedbed. It was placed on top of a set of six sieves of 4.5, 2.8, 2.0, 1.0, 0.6 and 0.3 mm, hanging from an arm that moved up and down 40 times per minute over a distance of 8 cm. The aggregates that remained on each sieve were allowed to oven dry and then weighed. The mean weight diameter was calculated as described under § 4.2.1.

Henin index of instability (Is)

The method described by Henin et al. (1958) was also used in our research. This method was developed to evaluate the behaviour of aggregates smaller than 2 mm diameter exposed to water action after a pre-treatment with ethanol, benzene or water. Results are expressed as an index that varies from 0.1 for the most stable soils to values higher than 100 for the very unstable (sodic) soils. This method has been frequently used in Uruguay, so it was included to compare results with those obtained by the wet sieving method previously described, in order to see which was giving better information and the possible reasons for that. To prepare the sample, it was first air-dried, then hand crumbled and passed through a 2 mm sieve. A complete description of the pretreatments, procedures and calculations is found in Burke et al. (1986).

4.2.3 Measurement of microbial activity

Microbial activity in soils includes all transformations of components of the soil that are caused by soil microorganisms (Bauer et al., 1991). The reason for including this determination in our research is that the end products of that activity are responsible for changes in structural status. Microbial respiration is defined as the release of CO_2 by the microbial population and it can be used as an indication of the microbial activity of the soil. A titrimetric analysis of carbon dioxide evolution was used, as described by Frioni (1990). Fifty grams of air-dried soil less than 2 mm diameter were brought under standard conditions of moisture (around 60% of the moisture content at field capacity) and temperature (30°C) in a closed system, and CO_2 allowed to be produced during one week. The CO_2 was trapped in NaOH and the remaining NaOH was titrated with HCl.

4.2.4 Measurement of compaction

Bulk Density

The bulk density was determined taking undisturbed core samples of 100 cm^3 and weighing these after drying in the oven at 105°C for 24 hours. Together with the determination of particle density, it was used to calculate the total porosity (Danielson and Sutherland, 1986).

Resistance to penetration

The resistance to penetration is not a particular property of a soil, but a summation effect of several properties of which bulk density, water content and shearing resistance are the most important ones (Burke et al., 1986). It is measured by pushing or driving an object into the soil. It can give some information about the force that roots will have to develop under a certain condition of soil, despite the poor analogy of a growing root finding its way through the soil with a generally much larger, rigid and comparatively fast penetrating probe. A Stiboka type penetrograph was used, which is a self-recording, static, cone penetrometer. A description of it can be found in Eijkelkamp (1988). A base surface cone of 1 cm^2 was used with a diameter of 11.28 mm. This was the smallest available and the only one that could be pushed into the clayey layers of the soils being studied. The cone angle was 60°. The rate of penetration was 2 cm s^{-1} and the measuring depth 75 cm except in cases where it was not possible to reach it. Results were obtained in N cm^{-2}. Moisture content of the profile was measured at several depths at the same moment.

4.2.5 Measurement of splash

For the determination of splash, plastic cups were installed in the plots. They allowed to obtain relative values for the different treatments. The surface area of the cups was 51.5 cm^2 (8.1 cm diameter) and the height was 10 cm. A rim of about 2 mm was kept above the soil surface plane in order to prevent the entrance of runoff water. The contact area between cup and soil was sealed to prevent the cups from changes in position. After a rainfall, the cups were collected, closed and transported to the laboratory in order to record the weight of soil particles collected (after drying them in the oven). Results were expressed in grams of oven-dried soil.

4.2.6 Measurement of soil losses

To measure soil losses, a small rainfall simulator developed by Kamphorst (1987) was used. Runoff and soil losses collected during application of an artificial rain with this device reflect the integrated effect of all the processes occurring during sheet erosion, as splash, swelling, slaking, crusting and sealing, infiltration and runoff, particle detachment and sediment transport. This method gives relative values of infiltration and runoff obtained in small plots (625 cm^2) and is not providing absolute rates of erosion losses in large areas. Drops are produced by means of water falling from a reservoir through 49 capillary tubes placed 40 cm above the soil surface. The simulated rainfall intensity obtained is 16 mm min^{-1}, lasting three minutes in total for each test. The intensity and the kinetic energy are much higher than under a real rainfall. These far from real conditions make this method valid only in relative terms. The small plots were prepared very carefully trying to avoid variations due to differences in soil handling.

4.2.7 Measurement of hydraulic characteristics

Infiltration capacity

The rate of infiltration is mainly dependent on moisture content, on texture and structure. With respect to the measurement of infiltration rates, this can be done with double-ring infiltrometers or with rainfall simulators. Considerable differences between the two methods can occur (Hoogmoed and Stroosnijder, 1984). Sidiras and Roth (1987) measured infiltration rates under different surface conditions on an Oxisol in Paraná, Brazil, using both methodologies.

For both methods, they found a strong positive correlation between soil cover percentage and infiltration rate, the double-ring infiltrometer producing much higher values than the rainfall simulator. When comparing tillage systems, they found that while under conventional tillage the infiltration rates were highest when measured with the ring infiltrometers, under no-tillage the highest rates were measured with the rainfall simulator. They explain this by the rapid formation of a surface seal when using a rainfall simulator in the plots under conventional tillage. In our research a double-ring infiltrometer was used to measure the infiltration, with a 30 cm outer, a 10 cm inner diameter, and a height of 15 cm. It was pushed 4 cm into the soil and a constant water layer of 7 cm was kept on top. Background of this methodology is described in Bouwer (1986). The infiltration rate was recorded until reaching a constant value, for a period no longer than 2 hours. Conditions were kept as homogeneous as possible, although the moisture content of the plots varied during the day and in subsequent days. For this reason, only the final data are used for comparisons between treatments, and not the whole curve. This determination is meant to give information about the amount of water that can get into the profile when a constant head of water is kept on top of it.

Soil moisture retention curve (pF)

The pF is defined as the minus log of the moisture tension in cm water. A combination of sand bins and pressure plates was used to cover the range of pF values selected to work with. From saturation until pF 2.7, the relationship was determined on undisturbed samples using sand bins. Higher pF values were obtained on aggregates in Wageningen, using pressure plates. Differences between treatments were studied as well as characteristics of the B horizon necessary as input values for the simulation model.

Saturated hydraulic conductivity (K_{sat})

To determine the saturated hydraulic conductivity, the constant head method was used, with cylinders of 100 cm^3, according to the principles described by Klute and Dirksen (1986), and adapted to the available equipment. It is a measure of the ability of a certain soil to transmit water, and varies depending on several soil characteristics as well as on the physical status. Together with pF and infiltration capacity, it determines the behaviour of the soil with respect to water.

Sealing index

The sealing index was developed by Roth (1992) and consists of a standardized index for comparing soils on their risk for seal formation and for comparing influences of different treatments in a certain soil. It is the ratio of the saturated hydraulic conductivity of an unsealed sample to that of a sealed one of the same origin. It is expressed as K_u/K_s where K_u is the K_{sat} of the unsealed sample and K_s the K_{sat} of the sealed sample. Sealing is obtained by exposing the samples to a certain amount of natural or simulated rainfall with a known kinetic energy.

In our research, samples were taken from the seedbed in cylinders of 300 cm^3 volume, as many as needed to have two groups of equal size for each treatment (six to twelve repetitions were performed in this work). One of the groups was exposed to simulated rainfall with a kinetic energy of 500 J m^{-2}. This energy was chosen after several test runs, where it proved to be the value at which an already distinguishable seal had formed without too much water accumulating on top of the sample. The K_{sat} was then measured for each sample from both groups. The averages per group were calculated and from these averages the index was calculated for each treatment. Rain was produced by means of a rainfall simulator adapted from Adams et al. (1957). Its characteristics are described in Table 9 and a scheme is presented in Fig. 6.

Table 9

Specifications of the laboratory rainfall simulator used to determine the sealing index (adapted from Adams et al., 1957)

Drop fall height (m)	3.41
Number of capillaries	180
Inner diameter capillaries (mm)	0.5
Drop diameter (mm)	5.15
Surface (m^2)	0.0658
Kinetic energy ($Jm^{-2}mm^{-1}$)	25.42

The simulator was of the drop forming type, with glass capillaries from which the drops fall down when reaching a certain weight. The set up of the equipment was done in order to obtain the desired kinetic energy (calculations were made according to Laws, 1941 and Wischmeier and Smith, 1987) and to resemble as close as possible the characteristics of natural rain. The simulations were done at an intensity of 30 mm h^{-1} during 40 minutes. The cylinders containing the samples were placed in a tray with iron wire and a cheesecloth bottom, filled with aggregates taken from the same plots, in order to simulate the process of splash erosion. A gentle swaying of the tray was applied to prevent drops from hitting the same spot every time.

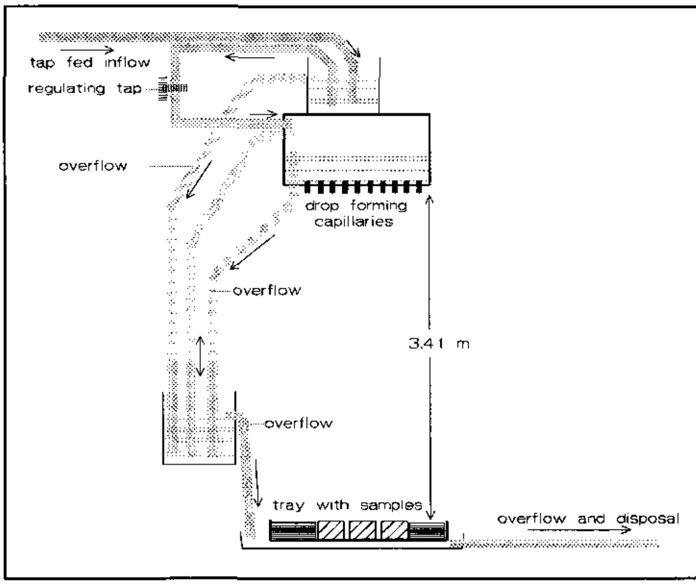


Fig. 6. Diagram of the rainfall simulator adapted from Adams et al.(1957)

4.2.8 Laboratory studies on the relation structure status - soil losses

A laboratory standardized procedure to study the relationship between soil structure status and soil losses by rainfall erosion was performed in laboratories of the Wageningen Agricultural University, as follows. Air-dried aggregates between 1 and 5 mm diameter were placed on sand bins and brought to the moisture content at pF 2. With those aggregates a range of pre-defined moisture contents was prepared (by drying them with an air drier or by carefully moistening them). A certain amount of each sample was placed in a cylinder of 100 cm^3 volume, and then compacted with a pressure up to 4 bar by using a constant velocity compression equipment, described in Dawidowski and Lerink

(1990). On these samples, the final height was precisely measured and the bulk density was calculated. Pore space (%) was calculated from bulk and particle density data. The Moisture - Pressure - Volume diagram (M-P-V) was obtained. This diagram expresses the resulting pore space (% v v^{-1}) versus the gravimetric moisture content at quick uni-axial compaction with a given load (Koolen, 1987).

Three parallel series of a range of moisture contents were prepared. In one of them, immediately after compaction, the air permeability was determined by means of an air permeameter (Perdok and Hendrikse 1982, calculations according to Kmoch, 1962). The samples were then saturated to measure hydraulic conductivity. In the second series, the samples were allowed to air dry. By gently crushing these samples, aggregates between 4.8 and 8 mm diameter were obtained. The wet sieving method was performed on these aggregates. The procedure for this determination was not exactly the same as described under § 4.2.2, because of small differences on the available equipment. Five sieves were used (4.8, 3.3, 2.0, 1.0 and 0.3 mm diameter) in this case. The equipment made 30 strokes per minute and moved over a distance of 2.5 cm.

The third set of samples was prepared for evaluation of splash, runoff and infiltration. These samples were prepared in bigger cylinders (8 cm diameter and approximately 250 cm^3 volume), and were exposed to raindrop impact under a rotating disc rainfall simulator described in De Klerk (1995) and in Hoogmoed and Stroosnijder (1984). Rainfall with an intensity as close as possible to 35 mm h^{-1} was applied during 30 minutes in order to obtain a kinetic energy of approximately 500 J m^{-2}. Each sample was placed in a sample holder as shown in Fig. 7, in order to separate infiltration (A), runoff (B) and splash (C). A group of 7 of these samples (the complete moisture range for one horizon) was placed on a rotating wooden tray under the simulator. This tray was regularly moved to prevent drops from always falling on the same spot and to allow that small variations in intensity could be evenly distributed. After the simulation, the saturated hydraulic conductivity was measured again, and the sealing index described in § 4.2.7 was calculated. In this way, the procedure was fully standardized and prevented some of the sources of variation described under field conditions.

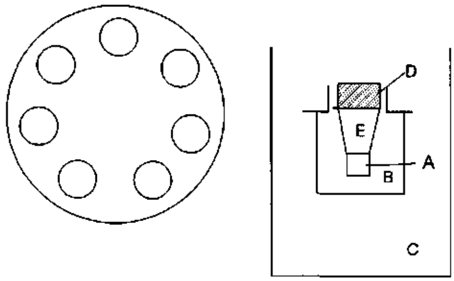


Fig. 7. Scheme of the set-up for the rotating rainfall simulator. Left: tray with samples (top view). Right: set-up for each sample (side view).

4.3 Modelling to predict soil behaviour towards rainfall

The model SWIM (Soil Water Infiltration and Movement) was selected to work with mainly because of its claims to work with the best possible solution to the infiltration problem, and to deal with layered soils. It is also easy and fast for running and the data on rainfall for Uruguay was easy to provide, as it was available in one hour periods. This model was built by P.J. Ross, in Australia, to simulate water infiltration and movement in soils. Water enters the system as precipitation and is removed by runoff, drainage, evaporation from the soil surface and transpiration by vegetation. It assumes that soil conditions are horizontally uniform, that flow is described by Richards' equation (Ross, 1990 a) and that soil hydraulic properties can be described by simple functions. It is a mechanistic model that incorporates essential physics mechanisms. It is claimed to have a good predictive capability that allows to extrapolate results at least in a qualitative sense (Bristow et al., 1994).

The major features of the SWIM include the ability of the model to deal with

- layered and gradational soils such as occur in the field, where hydraulic properties may vary with depth down the profile, either abruptly or gradually,
- saturated/unsaturated conditions as can occur at layer interfaces, and which result in locally perched water,
- surface ponding as can occur under high rainfall intensities,
- surface sealing, where properties at the surface layer may vary directly as a function of rainfall energy, and hence indirectly as a function of time,
- rainfall dynamics, so that real storm intensities (down to 1-minute resolution) can be dealt with in the simulations.

5 RESULTS AND DISCUSSION

5.1 Field and laboratory results under natural conditions

5.1.1 Introduction

As a first overview, an analysis of principal components for the tillage - rotation experiment is performed showing that all the variables selected are contributing (to a similar extent) to the general variance and are worth to be analyzed separately. This is also confirmed by means of a multiple correlation analysis where yield components are included. Thus, a discussion will follow for every variable to indicate its relevance. Statistical analyses, where relevant, are presented in Appendix IV (from a to w).

5.1.2 Effects of management on physical-microbiological characteristics

Seedbed quality

The mean weight diameter (DSD: dry sieving diameter in mm) obtained with samples from the seedbed in the tillage - rotation experiment is presented in Fig. 8 (the description of the treatments is in Table 6). The graph on the left shows higher values for reduced (RT) and vertical tillage (VT) than for conventional (CT), significant at 5% level. The graph on the right shows the results in relation to rotation systems. The plots where sunflower is buried (W-S) show a higher dry sieving diameter, while the other rotations do not show differences. There are no data on the amount of green biomass incorporated for the different treatments, but it is likely that sunflower (because of stalks) takes longer to decompose and that binding effects last longer than for other crops.

In literature, Kouwenhoven (1986) working in the laboratory on three soils with a clay content varying from 4 to 36%, showed that the mean weight diameter of freshly tilled soil decreases with an increase in the working intensity. However, Comia et al. (1994), working in Sweden on clay and clay loam soils showed no difference between tillage systems (conventional and reduced). They found that under both systems, seedbed conditions did not limit emergence although other growth conditions caused a higher yield under reduced tillage. Ghidey et al.

(1985) report lower rates of decomposition for sunflower when compared to soybean and corn. They relate the result to the C/N ratio. The lower the ratio, the faster the residue decay.

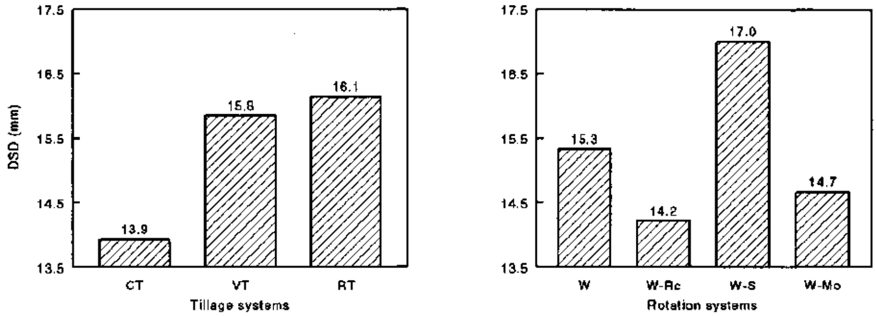


Fig. 8. *Tillage and rotation effects on seedbed quality. (Key to symbols: DSD: dry sieving diameter (mm); CT: conventional tillage; VT: vertical tillage; RT: reduced tillage; W: continuous wheat; W-Rc: wheat-red clover; W-S: wheat-sunflower; W-Mo: wheat-moha)*

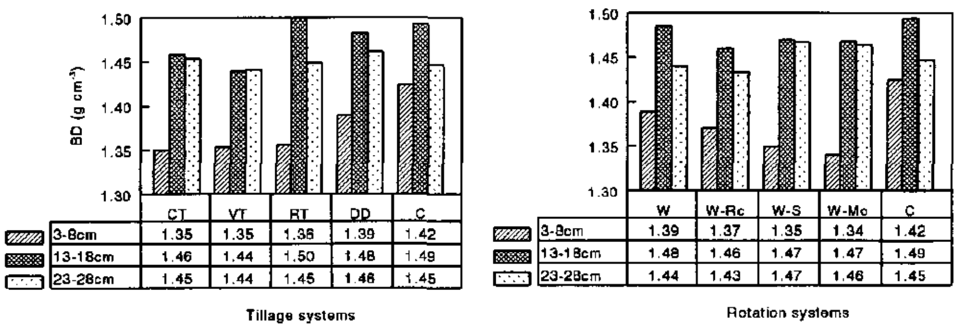
For our research, VT and RT result in bigger seedbed aggregates compared to CT, and the crop rotation W-S result in bigger seedbed aggregates compared to the other rotations studied. Just this information is not enough, but other measurements are needed to know whether this indicator of seedbed quality has an influence on erosion risk.

Density and porosity

a) Tillage - rotation experiment

Fig. 9 shows the bulk density values for the three layers described in § 4.1.1. The sampling was done a few days before harvesting the barley in December 1991, in order to avoid the effects of recent tillage. By the end of the crop period, only more stable effects of the different tillage systems were expected to be evident. The values obtained in the top layer are always higher than the value reported by Brown et al. (1992) as optimum for root growth (1.21 g cm^{-3}) in similar soils. Below 10 cm depth our values are around 1.47 g cm^{-3}, a value reported as critical by the authors mentioned.

Layer 3 to 8 cm depth - There is a slightly lower bulk density under the different tillage systems when compared to DD (graph on the left), though not statistically significant. Bulk density under continuous wheat (graph on the right) is higher than for the other rotations. When looking at the results for individual treatments (multiple range analysis in Appendix IV), DD plots under W and W-Rc show the highest values for bulk density, while those under W-S and W-Mo show the lowest. This is an indication of a positive effect due to the combination of the tillage system (DD) and the root systems of sunflower and moha in this layer. The control plot C shows a significantly higher value.



	CT	VT	RT	DD	C
3-8cm	1.35	1.35	1.36	1.39	1.42
13-18cm	1.46	1.44	1.50	1.48	1.49
23-28cm	1.45	1.44	1.45	1.46	1.45

	W	W-Rc	W-S	W-Mo	C
3-8cm	1.39	1.37	1.35	1.34	1.42
13-18cm	1.48	1.46	1.47	1.47	1.49
23-28cm	1.44	1.43	1.47	1.46	1.45

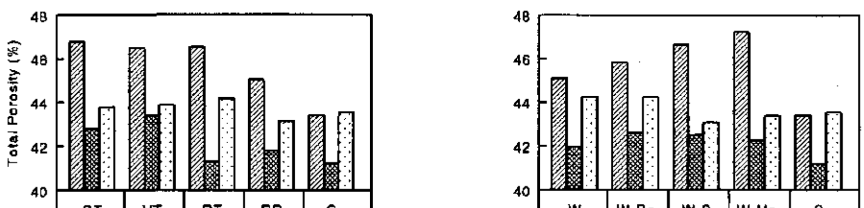
Fig. 9. Tillage and rotation effects on bulk density. (Key to symbols: BD: bulk density; CT: conventional tillage; VT: vertical tillage; RT: reduced tillage; DD: direct drilling; C: control plot sown with fescue; W: continuous wheat; W-Rc: wheat-red clover; W-S: wheat-sunflower; W-Mo: wheat-moha)

Layer 13 to 18 cm depth - Bulk density is always higher in this layer than in the top layer. This is a result of the working depth of every primary tillage implement; always around 15 cm depth. Tillage systems caused significant differences in this layer. Fig. 9 (left) shows that reduced tillage and direct drilling lead to higher densities, while CT and VT have caused some reduction in density. Rotation systems do not show any effect in this layer.

Layer 23 to 28 cm depth - In this layer differences are negligible.

Vivas (1992) reports determinations of bulk density in three silty loam soils in Argentina, where from 0 to 15 cm depth, the bulk density was higher under direct drilling than under CT (1.33 and 1.24 respectively) during a three year period. Douglas et al. (1992) working on a clay loam imperfectly drained with 22% clay in the topsoil, found after four years of establishment of a perennial grass crop, that even under several compaction levels, the bulk density of the layer close to the soil surface tended to be lower than in the first year. The reduction was greatest in a relatively heavily compacted soil. Horne et al. (1992) working on a silt loam in New Zealand found the lowest value for natural pasture in the top 20 cm layer (1.10 g cm^{-3}), the highest under zero tillage (1.41) and no difference between conventional and minimum tillage (1.31 and 1.32 respectively).

The positive effect reported in literature by long term pastures, cannot be seen in our experiment after four years of fescue. For years, the whole field had been devoted to agriculture, and according to these results, three years without tillage are apparently not enough to lower the values for bulk density, not even when sowing a permanent pasture as fescue.



	CT	VT	RT	DD	C
3-8 cm	47	47	47	45	43
13-18 cm	43	43	41	42	41
23-28 cm	44	44	44	43	44

Tillage systems

	W	W-Rc	W-S	W-Mo	C
3-8cm	45	46	47	47	43
13-18cm	42	43	42	42	41
23-28cm	44	44	43	43	44

Rotation systems

Fig. 10. Tillage and rotation effects on total porosity. (Key to symbols: see Fig.9)

Fig.10 shows the values obtained for total porosity. As this characteristic depends also on particle density, it provides a more specific definition for the status of a certain soil type, and allows an easier comparison among the different sites. Values of particle density are 2.532, 2.548 and 2.577 g cm^{-3} for the layer 3-8, 13-18 and 23-28 respectively, with a standard deviation of 0.02 in every case.

b) Summer green manuring experiment

Bulk density and total porosity values for the summer green manuring experiment are summarised in Table 10 (treatments description in Table 7). In the top layer, the bare kept plot has a slightly higher bulk density. The opposite is found in the layer 15 to 20 cm depth. Both results can be explained by the incorporation (with hand implements) of the crops, done within a layer of around 15 cm depth. At up to 20 cm depth, the lowest bulk density is found in the plots where sorghum was buried. When all depths are observed, the lowest values occur in the plots where crotalaria was buried.

Table 10
Bulk density and total porosity for the summer green manuring experiment, bare kept plot and an average of all the plots with buried crops

Treatment	*Bulk density (g cm^{-3})*			*Total porosity (%)*		
	*0-15**	*15-20*	*B hor*	*0-15*	*15-20*	*B hor*
bare	1.31	1.46	1.74	48	44	34
Avg others	1.26	1.50	1.68	51	42	36
sd	0.07	0.06	0.07	0.02	0.02	0.03

*(*Depths of sampling described under § 4.1.2)*

Boni and Espíndola (1991) working on a compacted Latossolo Roxo found that crotalaria and guandú caused a decrease in the bulk density of the top layer (crotalaria brought it from 1.3 to 1.2 and guandú from 1.3 to 1.1) as well as in the subsoil layer (from 1.5 to 1.3 and from 1.5 to 1.4 respectively; values expressed in g cm^{-3}).

For the B horizon, the plots under sunflower and crotalaria show a lower bulk density, thus higher porosity. The root system of sunflower consists of one strong deep growing main root that can have an influence on these values. Crotalaria is a legume and has a deep growing root system as well. In general, bulk density in the B horizon is extremely high in this site. This is one of the characteristics that shows the difficulties that this argillic horizon poses for root growth, conductivity for water, as well as for management decisions.

c) Winter green manuring experiment

Only the top layer was sampled in this experiment (treatments description in Table 8). Bulk density is again slightly higher in the bare kept plots when compared with an average of the others (1.16 and 1.10 g cm^{-3} respectively). This experiment has been prepared for sowing by means of hand tools. This, together with the need for a continuous cleaning of a weed (*Cyperus rotundus*) could be the reason for the small density differences in these results.

In the top 20 cm layer, values of bulk density are similar in the sites where the tillage - rotation and the summer green manuring experiments were carried out, although according to the textural characteristics of both sites, values for the latter would be expected to be higher (sandy texture). This is an indication of a difference in structure status of both sites. The B horizon shows an extremely high density at the site of the summer green manuring experiment. In the tillage - rotation experiment, there is neither evidence of a decrease in bulk density due to reduced tillage, nor due to a four year pasture. In the three experiments, a decrease in bulk density is evident due to the action of roots and to the mixing of crops into the soil. The crops that show to have the best effects are sunflower and crotalaria.

Aggregate stability and respiratory activity

i) Wet sieving diameter (WSD)

a) Tillage - rotation experiment

Values obtained with the wet sieving analysis for the tillage - rotation experiment, are shown in Fig.11.

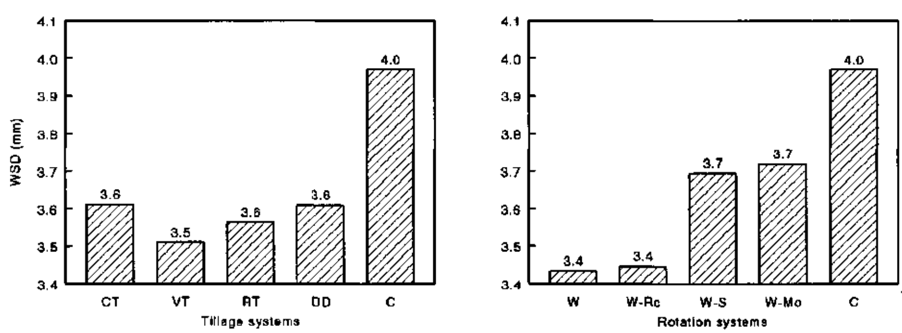


Fig. 11. *Tillage and rotation effects on the stability of structure expressed by the mean weight diameter after wet sieving (WSD). (Key to symbols: see Fig. 9)*

No change can be reported due to tillage systems (left). Significantly higher values are found on the plots where sunflower and moha are incorporated (right). The values for the control plots (sown with fescue) are always the highest. This would mean that every tillage operation is causing about the same degree of damage to the structure, even when mainly traffic is implied (direct drilling). Incorporation of green biomass or sowing of a permanent pasture with limited traffic clearly showed an improvement.

Thorburn (1992) working with a Vertisol did not find significant differences in the stability of aggregates with different tillage systems. Bickerton (1988) working on an imperfectly drained brown forest soil of a sandy loam texture and on a

sandy silt loam, reports differences showing the influence of tillage systems, for a long-term experiment lasting 20 years. His results indicate that both increases in aggregate stability and resistance to compaction can be achieved by long term direct drilling or by shallow cultivation in conjunction with straw incorporation in the top 10 cm soil. Dexter (1991) refers to processes occurring in high clay content soils and states that ageing of soil after disturbance, and grass roots, cause an increase in the stability and in the resistance to further disruption. Kay et al. (1994) for a fine sandy loam in South Australia, report that wet aggregate stability is responsive to management (different rotations) and that at 0 to 5 cm it shows a significant positive correlation with organic carbon content. Kochhann and Denardin (1992) report that water stable aggregates larger than 4.76 mm vary from 96% in natural forest to 35% in DD, 11% under conventional tillage with straw incorporation and 3% when burning the straw. Horne et al. (1992) on a silt loam soil in New Zealand found similar results. They report that under conventional tillage, the decline was steady during the 10 years that the experiment lasted compared to a pasture site, while under minimum and zero tillage, the decline occurred during the first two years of cropping performed on all the plots before starting with the different treatments.
Most likely the duration of our experiment was not enough to show improvements due to direct drilling, as described in the literature.

b) Summer green manuring experiment

In the summer green manuring experiment, the bare kept plots show the lowest wet sieving diameter. The amount of green material incorporated was measured, and expressed as well in weight of dry material. Table 11 shows the results, as an average for the three blocks.

Values of the wet sieving diameter are always quite low when compared to those obtained for the tillage - rotation experiment, showing that this soil has a weaker structure due to its sandy texture. This is also possibly due to the delay that occurred in the case of the tillage - rotation experiment between the sampling and the performance of the analysis (ageing of aggregates referred by Dexter, 1991). Sunflower, sorghum and jack bean produce the highest amounts of materials to be incorporated. On the other hand, the crops that led to higher wet sieving diameter are legumes, mainly crotalaria. This can be related to the C/N ratio. Hadas et al. (1994), working on a silty loam of loessial origin in Israel found an immediate effect on stability and strength upon addition of residues with a high C/N ratio, but this effect only persisted for a short period of 1-3 weeks, while residues with a moderate C/N ratio helped to stabilize the structure for longer periods. They conclude that a proper management of amounts and C/N ratio of residues can provide the farmer with some measure of control over soil structure. In our research, crops were buried in April 1993 and samples for wet sieving were taken in late June. Crops like crotalaria and jack bean will have an intermediate C/N ratio (based on their characteristics) when compared to sorghum or sunflower (around 60) and to red clover (around 25). Values for the C/N ratio vary a lot, depending on the time of sampling.

Table 11

Results of wet sieving diameter, amounts of green and dry material incorporated in the summer green manuring experiment, and organic matter determined by the method of Walkley and Black

Treatment	*Wet sieving diameter (mm)*	*Green matter (tons ha^{-1})*	*Dry matter (tons ha^{-1})*	*Organic matter (%)*
1 *Canavalia ensiformis* (jack bean)	1.00	64.1	12.1	2.6
2 Bare kept plots	0.54	0	0	2.7
3 *Setaria italica* (moha)	0.83	25.6	10.7	2.7
4 *Sorghum bicolor*	0.87	64.7	16.8	2.6
5 *Vigna ungüiculata* (cowpea maní)	0.87	32.8	5.7	2.6
6 *Cajanus cajan* (guandú)	0.75	22.8	7.5	2.5
7 *Crotalaria juncea* (crotalaria)	1.06	29.6	8.6	2.8
8 *Helianthus annuus* (sunflower)	0.74	83.3	15.8	2.7
9 *Vigna ungüiculata* (cowpea moro)	0.93	31.5	5.2	2.1

With respect to the amount of soil organic matter, as determined by the method of Walkley and Black (Blakemore et al., 1972) shown in Table 11, we found no close relationship with the wet sieving diameter. This is in agreement with results reported by Haynes and Knight (1989). Working with one stony silt loam and with a clay loam in New Zealand, they report higher results of aggregate stability under no tillage even at depths where organic matter content was higher under conventional tillage. This suggests that within the soil profile the distribution of specific binding agents involved in aggregate stability is different to that of total soil organic matter. Carter (1992) worked on fine sandy loam soils in Canada, all of them with the same texture, in order to relate the changes in aggregate stability to differences in organic matter content. He found that the mean weight diameter of aggregates after wet sieving was 33% and 55% relative to the grassland sites, for mouldboard plough and direct drilling respectively. This was linearly related to the increase of soil organic carbon by 10% under direct drilling relative to mouldboard plough. Haynes and Swift (1990) for two silt loam soils in New Zealand observed large fluctuations in aggregate stability under mixed cropping rotations (2-4 years grazed pasture followed by 2-4 years arable cropping), even though total soil organic matter remained relatively constant. In our work, the cropping rotations are too short for a build-up of higher organic matter values, but the occurrence of some aggregation caused by organic residues which cannot be detected by the Walkley Black method is possible, yet increasing the aggregate stability values.

c) Winter green manuring experiment

In the winter green manuring experiment there is also a positive effect of green material incorporated, on the stability of structure as measured by the wet sieving analysis (Table 12). The bare kept plot has a lower value when compared to plots where avena negra and serradela were incorporated. These crops are those yielding significantly higher amounts of green residues. Plots where alfalfa was buried show a high wet sieving diameter as well, although the amount of green residues for this crop was lower. This is possibly due to the fact that the incorporation of alfalfa took place later than the others, and that the positive effects would diminish when a longer period of bare kept soil follows the incorporation of the green material.

Legumes (serradela and alfalfa) show a positive effect in our research. Kemper and Derpsch (1980/1981) report that leguminous cover crops have no difficulty in penetrating compact layers. This enhances the biological activity and improves the structure status. McVay et al. (1989) working with two different soils (a gravelly clay loam and a sandy clay loam soil) in USA and with several winter legumes as cover crops, found more water-stable aggregates in the top layer following cover crops than fallow.

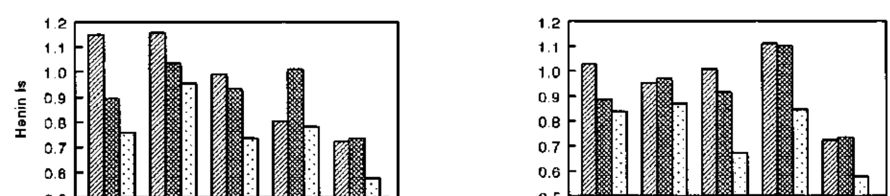
Table 12

Results of the wet sieving diameter, amounts of green and dry material incorporated in the winter green manuring experiment

Treatment	*Wet sieving diameter (mm)*	*Green matter (tons ha^{-1})*	*Dry matter (tons ha^{-1})*
1 Bare kept plots	0.99	0	0
2 *Secale cereale* (rye)	1.08	6.2	1.9
3 *Medicago sativa* (alfalfa)	1.84	4.7	1.1
4 *Spergula arvensis* (espérgula)	1.04	7.7	1.8
5 *Avena strigosa* (av. negra)	1.34	13.8	2.4
6 *Ornithopus sativus* (serradela)	1.36	14.0	2.6

ii) Henin index of instability (Is)

The Henin index of instability was determined in the tillage - rotation experiment, and results are presented in Fig. 12. There are effects of tillage systems (left) in the top 3 to 8 cm layer, the seedbed. Direct sowing and plots sown with fescue show significantly lower values (higher stability). For the deeper layers, there are no differences between plots. The deepest layer is always significantly more stable than the top layers. The different rotations do not significantly affect this index (Fig.12 right).



	CT	VT	RT	DD	C
3-8cm	1.1	1.2	1.0	0.8	0.7
13-18cm	0.9	1.0	0.9	1.0	0.7
23-28cm	0.8	1.0	0.7	0.8	0.6

Tillage systems

	W	W-Rc	W-S	W-Mo	C
3-8 cm	1.0	1.0	1.0	1.1	0.7
13-18 cm	0.9	1.0	0.9	1.1	0.7
23-28 cm	0.8	0.9	0.7	0.8	0.6

Rotation systems

Fig. 12. *Tillage and rotation effects on the Henin index of instability (Is). (Key to symbols: see Fig. 9)*

The index values obtained with this method are low in general meaning that stability is quite good for all layers. In Uruguay Bak and Cayssials (1974) made several determinations using this method and they reported values lower than 0.5 for stable soils (high organic matter content Vertisols) and higher than 5 for unstable soils (Solonetz). The characteristics of the soil in this experiment (high clay and high organic matter contents) lead to highly stable aggregates smaller than 2 mm diameter. Burke et al. (1986) state that this method is not suitable for predicting short term evolution of systems affected by rainfall impact and initial moisture content. Our research showed that this is a sensitive test to evaluate the effects of intensive tillage, only in the surface layer.

A comparison between the results obtained with the wet sieving analysis (WSD) and with the Henin method (Is) was attempted. The average of the Henin index for the top and second layers was calculated, and a regression analysis was performed with the wet sieving results. It showed no relationship between both values. While the Henin index shows the negative effects of intensive tillage, the wet sieving analysis, as it is performed on bigger aggregates, seems to better show the benefits of the incorporation of green biomass in binding aggregates.

iii) Biomass respiratory activity (BRA)

Results of the biomass respiratory activity in two layers of the summer green manuring experiment (0 to 15 and 20 to 40 cm) are shown in Fig. 13.

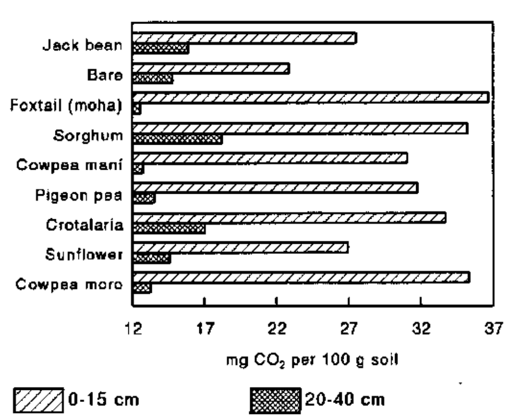


Fig. 13. *Soil biomass respiratory activity (mg CO_2 per 100 g soil) in two depths for the summer green manuring experiment.*

There are significant differences between both layers but not between treatments. Still, sorghum and crotalaria, both with deep growing root systems, show high values in both layers measured. Values for moha and cowpea moro are high in the top layer. Cowpea is a legume with good root nodulation, possibly leading to this high value. Moha develops most of its root system in the top 20 cm layer.

Hendrix et al. (1988) report that the type of residue can have a strong effect on soil respiration. They describe residues of clover as more easily decomposable than those of rye. Systems with legume-N inputs have higher respiratory activity throughout the year than rye systems which received fertilizer. They found that long-term effects of residue quality on nutrient cycling and soil organic matter may be significant. When considering the relationship between microbial activity and structural stability, Hart et al. (1988) working on a silt loam in New Zealand, found that stability changes are more closely related to changes in microbial biomass carbon than to total organic matter.

In our research, there is no clear relationship between microbial activity and structural stability when a regression analysis is performed, while in literature, Carter (1992) reports a linear relationship between both parameters. Our results show a consistent positive effect of the incorporation of crotalaria and sorghum (as green material) on physico - microbiological status.

Resistance to penetration

Determinations of resistance to penetration were done up to 70 cm depth for the tillage - rotation experiment and for the summer green manuring experiment. The time for doing these determinations was shortly after enough rain had fallen in order to allow for the profiles to be at about field capacity all through their depths, thus trying to diminish the effect of the different moisture contents under the several treatments. Penetration resistance is highly influenced by moisture content. It is affected by the amount of water kept by the soil under a certain suction, and this depends on texture and structure (Taylor and Gardner, 1963; Taylor et al., 1966; Barley et al., 1965; Mirreh and Ketcheson, 1972). They state that % clay and mechanical resistance have a positive relationship when the soil is at field capacity or drier.

For the tillage - rotation experiment, results are shown in Table 13 up to 35 cm depth. The plots under fescue (C) are the most resistant all through the profile, partly due to a lower moisture content. With respect to tillage systems, in the top 10 cm there are no differences, but from 10 to 20 cm a positive effect of vertical tillage is found (lower values for penetration resistance), which is consistent with the lower values found for bulk density. As for rotation systems, red clover when included, shows also a positive influence all through the profile, when compared to continuous wheat.

Table 13

Resistance to penetration (N cm^{-2}) with depth for the tillage - rotation experiment (Key to symbols: see Fig. 9)

Depth (cm) *Treat*	*0*	*5*	*10*	*15*	*20*	*25*	*30*	*35*
W	1	10	25	50	71	105	115	107
W-Rc	0	7	19	40	50	82	99	105
CT	0	10	24	41	52	81	99	105
VT	0	10	22	33	39	91	110	108
RT	1	5	21	62	91	109	110	106
C	0	54	85	108	127	125	114	106

For the summer green manuring experiment (Fig.14) there is a general tendency significant only in some depths, of jack bean to cause a reduction on this resistance below 30 cm depth, even up to a depth of 80 cm. Crotalaria is in every depth within the lowest range of values (although not significantly, thus not shown in the figure). It can then be qualitatively concluded that vertical tillage and some species (mainly legumes) cause improvement on this soil characteristic.

The effects of green manure crops can be considered a sort of biological tillage. According to Dexter (1991), biological tillage aims at creating biopores for use by subsequent crops. Biopores are created by roots of plants able to penetrate compacted soils. Hulugalle et al. (1986) worked on an Oxic Paleustalf in Western Nigeria and compared the physical properties developed after the use of mucuna (legume) as a cover crop, with those developed under cropped plots with maize and cowpea. They report decreases of penetration resistance of 1.9 to 9.6% under mucuna, with respect to the cropped plots.

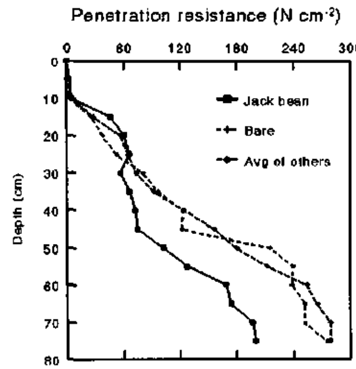


Fig. 14. Penetration resistance (N cm^{-2}) for the summer green manuring experiment.

Our results are in agreement with Cassel (1985). Working on a layered soil in Norfolk (USA) with a sandy Ap horizon overlaying a sandy clay loam B, he found a significant decrease in penetration resistance and an increase in depth of the unimpeded rooting zone, when comparing chisel and subsoiling vs conventional tillage. Thorburn (1992) found no differences below 15 cm depth in a Vertisol under different tillage systems (no tillage, mouldboard plough and disc plough). Carrasco (1989) worked in an experiment in which two highly different levels of compaction were created. He found significant differences in mechanical resistance in the top 25 cm layer. Malhi and O'Sullivan (1990) working with different soils in Alberta, Canada, report consistently greater mechanical resistance on zero-tillage than on conventional tillage plots, in the top layer (from 3.5 to 10.5 cm depth).
According to our results, the use of the chisel plough (VT) shows a positive effect when the actual physical status of the soil is poor.

5.1.3 Effects of soil management on crop behaviour

Tillage - rotation experiment

For the tillage - rotation experiment, several yield components of the main winter crop included in the rotations were determined in 1988 (wheat), 1989 (wheat) and 1991 (barley). One of them was the emergence (*number of plants per m^2*). Fig. 15 shows the results as an average for the three years.

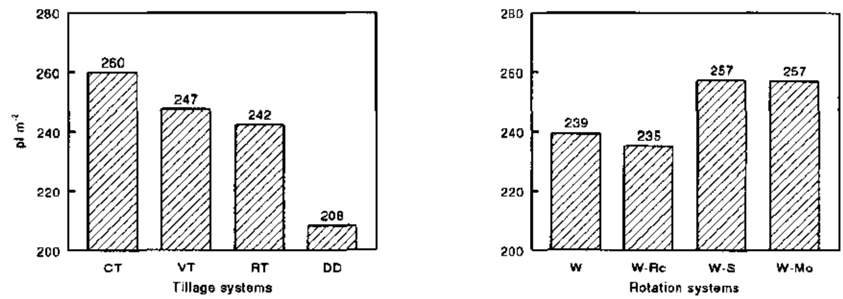


Fig. 15. Tillage and rotation effects on emergence (pl m^{-2}) of the main winter crop. Averaged values for 1988, 1989 and 1991. (Key to symbols: see Fig. 9)

With respect to tillage systems, CT shows a higher number of plants (Fig. 15 left) for the three years. The effects of the rotation systems (right) are not consistent through the years. The graph on the right shows that on average, when red clover is included, the emergence is lower. But this effect is not appearing under CT, indicating that when the green biomass of red clover is fully incorporated into the soil by intensive tillage, it does not produce negative effects. Reasons mentioned for the negative effect of the incorporation of red clover on the emergence of the next crop are phytotoxines and/or the development of fungi from legume decomposition (Almeida et al., 1991). The rotation W-S consistently shows a higher plant density, which is possibly due to a favourable C/N ratio of the residues of sunflower, and its effects on the seedbed quality (as discussed in § 5.1.2).

Other components of yield were studied, such as number of ears per unit surface, number of grains per ear, weight of 1000 grains, yield of grain and of dry matter both expressed in kg ha^{-1}. They do not show any significant effect of management system (either tillage or rotations). The grain yield is presented in figure 16 for 1988 and 1989. It shows neither influence of rotation nor of tillage system, except for direct drilling, where yields are lower for both years. In 1989 yields are in every case lower than in 1988, except for the case of direct drilling.

Derpsch et al. (1986, 1991) show results of several years of research in different soils in Paraná, Brazil, where yields of wheat were 19% higher under no-tillage and 6% higher under chisel ploughing, while soybean yields were

34% higher under no-tillage and 7% under chisel ploughing when compared with conventional tillage. They report higher yields under direct drilling from the beginning of the experiments. The reasons they mention for these higher yields are higher moisture content, lower soil temperature and higher biological activity. Results are then dependent on the specific soil and climatic conditions. In Brazil climatic conditions enhance mineralization. In Uruguay (with a cooler climate) in the site being studied, tillage appears to be necessary to improve conditions in order to obtain a high yield. The fact that yields under DD do not decrease in 1989 compared to 1988 while they do decrease under the other tillage systems, needs more years of research to show that it is a stable and positive tendency.

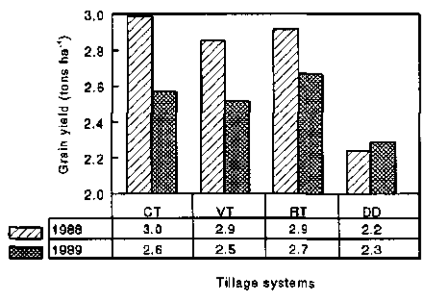


Fig. 16. Yield of winter wheat in tons of grain per ha for 1988 and 1989. Tillage - rotation experiment. (Key to symbols: see Fig. 9)

Blevins (1984) refers to several experiments where soils with slow internal drainage are not well suited for direct drilling. He mentions several reasons such as low soil temperatures, loss of nitrogen, disease damage and insect damage to plants during a time of reduced vigour and poor growth following rainy periods. A higher level of management will be required to use no-tillage on these soils, considering planting dates, plant populations and management of N fertilizer. In general, reduced tillage and stubble retention systems are reported to produce equivalent or sometimes higher yields compared with conventional tillage systems over a wide range of environmental conditions (Ellis et al., 1982; Francis et al., 1987). On the other hand decreases in root density (Whiteley and Dexter, 1982) and yield (Anaele and Bishnoi, 1992) under no tillage systems have been reported as well.

Because no yield differences have been detected, it is not possible in this research, to define clear relationships between yield and physical aspects. As emergence of plants showed variations depending on treatments, it was chosen to be related to the seedbed quality. A linear regression analysis was performed between emergence in 1991 and the dry sieving diameter (DSD). It showed a negative relationship, significant at 5% level. Although the influence of tillage systems is evident at emergence, later in the crop cycle many other factors play a role to compensate this condition. This is in agreement with Ciha (1982), who reports that a lower emergence due to different tillage systems will be compensated by a higher weight of grains.

In this research the quality of sowing was poorer in direct sowing than in the other tillage systems. Besides some small technical problems, the sowing was performed for all treatments the same day, when direct drill plots were relatively wetter. In these conditions, a good coverage of the seeds was not possible. In heavy textured soils, the timing of direct sowing as well as the timing of every tillage operation have to be adapted.

Summer green manuring experiment

In the summer green manuring experiment, barley was sown after the partial burial of the green materials and yields are presented in Fig. 17.

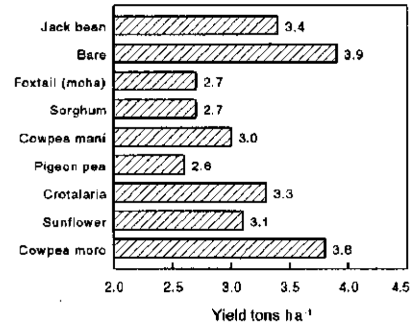


Fig. 17. *Yield of barley (tons ha^{-1}) for the summer green manuring experiment.*

Although yields were slightly higher under bare kept plots, differences are not statistically significant. There are also no clear relationships between yield and physical parameters.

Explanations of the effects of changes in soil physical parameters on yields are not a direct aim of this research. This information is presented as a support of our belief that adoption of techniques as reduced tillage and/or crops as green manures do not negatively affect yields of crops that follow. This is, in most cases, what we found with our research, except for the case of direct drilling, already discussed.

5.1.4 Effects of management on detachment and soil losses by runoff

Splash (particle detachment)

Splash was collected for the tillage - rotation experiment in every plot where tillage was performed, except in the plots under direct drilling or with fescue, assuming that under the grass and/or residue coverage of the DD and fescue plots, splash would be negligible. Three rainfall events occurred immediately after sowing the barley, 10.9, 25.9 and 32.0 mm in August 27th, September 1st and September 7th respectively. In these three cases the cups were placed and the splash weighed. Results are presented in Fig. 18, as the average of the three determinations. Splash tends to be higher under CT (left), although the difference is not statistically significant. For rotation systems (Fig. 18 right), the wheat - red clover shows a significantly lower detachment, partly due to the amount of residues on top of the plots. This presence of residues was observed, although not quantified. Rotations of wheat with sunflower and moha show the highest values.

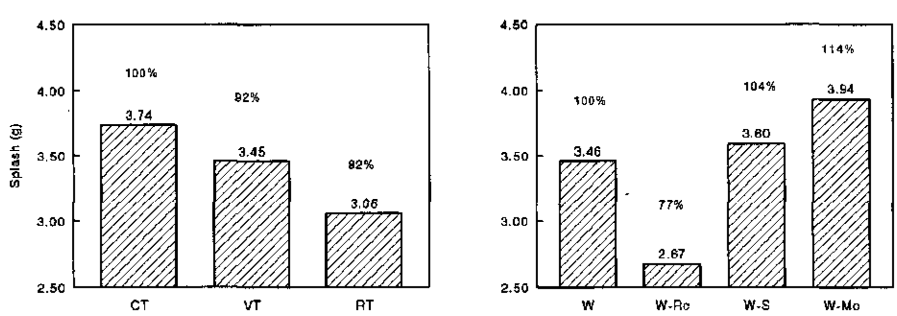


Fig. 18. Tillage and rotation effects on splash expressed in grams (dry soil) collected per cup and in relative amounts, compared to CT and W. Average of 3 measurements. (Key to symbols: see Fig. 9)

For the summer green manuring experiment, higher amounts of splash were measured in the bare kept plots when compared to all other plots. Measurements were done when the barley crop was already established, so there were no apparent crop residues on top. In Table 14, the results of particle detachment by rainfall splash are shown, expressed as percentages of bare kept plots.

Table 14

Relative amount of splash compared to bare plots, after one rainfall event in the summer green manuring experiment

Treatment		%
1	*Canavalia ensiformis* (jack bean)	79
2	Bare kept plots	100
3	*Setaria italica* (foxtail, moha)	66
4	*Sorghum bicolor*	63
5	*V. ungüiculata* (cowpea maní)	64
6	*Cajanus cajan* (pigeon pea, guandú)	57
7	*Crotalaria juncea*	60
8	*Helianthus annuus* (sunflower)	65
9	*V. ungüiculata* (cowpea moro)	68

The above results indicate that cover of soil surface, reduced tillage and incorporation of crops as green manures, are efficient tools to reduce the risk of erosion. In agreement with this, Derpsch et al. (1986) working in Paraná, Brazil, concluded that no-tillage in combination with adapted cover crops and crop rotations demonstrates a production system which is efficient in reducing water runoff and consequently soil erosion.

Regression analyses were performed with the purpose of quantifying the effect of physical properties on splash, but strong correlations were not found. For the tillage - rotation experiment, the relationship between splash and dry aggregate size distribution (dry sieving diameter expressing seedbed quality) although negative after the first rain, is not significant. The relationship between the wet sieving diameter (expressing structure stability) and the amount of splash in this experiment is positive, without statistical significance. Results reported in literature are contradictory. Luk (1979) working on several soils in Australia, found the wet aggregate stability to be the most significant property explaining soil loss by splash and runoff. Bollinne (1978) working on a grey-brown podzolic soil with high silt content in Belgium states that splash is higher on the better structured soils. This is explained by him and by Mazurak et al. (1975) by the easier detachment of stable aggregates of better structured soils in the one hand, and by the strength of crusts developed under low stability conditions for poorly structured soils on the other hand.

A positive, although weak relationship was found between the Henin instability index and the amount of splash. This was found on small (<2 mm) aggregates (the more unstable causing greater splash). However, also bigger aggregates, found relatively stable by the wet sieving analysis, appeared to be more easily disrupted by rainfall. It can be observed that the wet sieving results are influenced by rotations (Fig. 11) more than by tillage systems, and that those rotations having the higher wet sieving diameter, show the higher amount of splash as well (rotations W-S and W-Mo).

In the summer green manuring experiment, the relationship between the wet sieving diameter and the amount of splash is negative. Being a sandy soil, the characteristics of the crust may not prevent detachment by rainfall. In addition, the period between the incorporation of crops and the recording of the splash was shorter for this experiment and it is possible that there is still some influence of the crop materials on the soil surface in reducing the splash. The amount of green material is negatively related to splash.

Soil loss

Results obtained with the small rainfall simulator for the summer and winter green manuring experiments are presented in table 15. In § 4.2.6 the Kamphorst simulator was described. The units tons ha^{-1} are used to express soil losses uniformly in this research, although because of the characteristics of the simulator, it does certainly not provide absolute rates of erosion losses in large areas.

There is a significant effect of treatments on sediment losses, that shows the benefits of green manure incorporation. In the summer green manuring experiment, soil losses are lowest after sorghum and after sunflower. It is possible that these two crops have the most stable residues, lasting longer on top of the soil and being more difficult to incorporate completely into the top layer, and may act as a mechanical barrier for rain drops. For the winter green manuring experiment, legumes (alfalfa and serradela) act more effectively in reducing soil losses. For a discussion on runoff, see page 81.

Table 15

Results obtained for the summer and winter green manuring experiments with the Kamphorst rainfall simulator, average for the three blocks with approximately 17 mm rain

Treatment		*soil loss (tons ha⁻¹)*	*runoff %*	*infiltration (100 - runoff)*
Summer green manuring experiment				
1	*Canavalia ensiformis* (jack bean)	0.9	28	72
2	Bare kept plots	1.4	40	60
3	*Setaria italica* (foxtail, moha)	0.9	29	71
4	*Sorghum bicolor*	0.2	6	94
5	*V. ungüiculata* (cowpea maní)	0.9	22	78
6	*Cajanus cajan* (guandú)	0.7	32	68
7	*Crotalaria juncea*	0.8	23	77
8	*Helianthus annuus* (sunflower)	0.5	19	81
9	*V. ungüiculata* (cowpea moro)	1.2	29	71
Winter green manuring experiment				
1	Bare kept plots	1.5	28	72
2	*Secale cereale* (rye)	0.7	24	76
3	*Medicago sativa* (alfalfa)	0.3	15	85
4	Spergula arvensis (corn spurrey)	0.8	19	81
5	*Avena strigosa* (avena negra)	0.4	21	79
6	*Ornithopus sativus* (serradela)	0.2	9	91

Several regression analyses are performed. A significant negative relationship exists between the amount of green material incorporated and the sediment losses (Fig. 19 left). There is a tendency (significant at 5% level in the winter green manuring experiment) to get higher losses when the wet sieving diameter is lower (Fig. 19 right). Soil loss is negatively related as well to biological respiratory activity in the summer green manuring experiment.

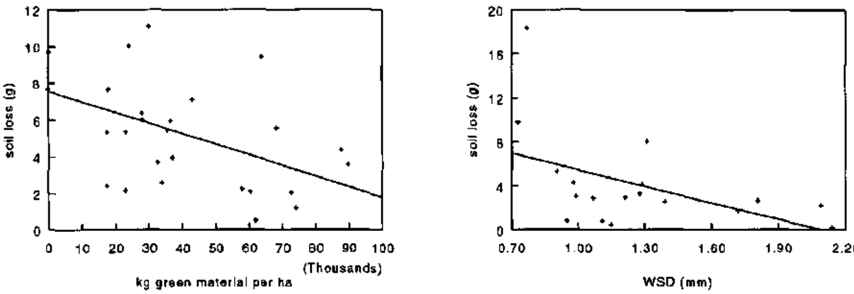


Fig. 19. Left: relationship between green material and soil losses measured with the Kamphorst rainfall simulator. Summer green manuring experiment, r^2 = 0.25.
Right: relationship between WSD and soil losses for the winter green manuring experiment, r^2 = 0.23.

Our results are in agreement with Luk (1979) who reports a negative relationship between structural stability and soil losses, and also in agreement with Klaij (1983) with data obtained in ICRISAT. He found that a cover crop reduces soil erosion often to less than one quarter of that under fallow treatment. Many authors refer to incorporation of residues. Brown et al. (1989) working on a moderately well drained soil with a silty loam A horizon and a silty clay loam B in USA, studied the influence of incorporating cornstalk residues, on rill erosion rates. Erosion was significantly reduced just after the incorporation of the residues, compared to the control treatment. Still 30 and 60 days after the incorporation, rill erosion was significantly lower in the areas where residues were incorporated.

5.1.5 Effects of management on hydraulic properties

Saturated hydraulic conductivity (K_{sat})

Saturated hydraulic conductivity (K_{sat}) was determined in the summer green manuring experiment in three layers as described in § 4.1.2. Results are shown in Table 16.

Table 16

Saturated hydraulic conductivity (K_{sat}) in mm day^{-1} in the summer green manuring experiment

Treatment		*2-7 cm*	*15-20 cm*	*B horizon*
1	*Canavalia ensiformis* (jack bean)	686	122	2
2	Bare kept plots	394	352	3
3	*Setaria italica* (moha)	670	117	0
4	*Sorghum bicolor*	960	151	3
5	*V. ungüiculata* (cowpea maní)	642	89	0
6	*Cajanus cajan* (guandú)	484	376	0
7	*Crotalaria juncea*	677	467	0
8	*Helianthus annuus* (sunflower)	832	70	8
9	*V. ungüiculata* (cowpea moro)	799	217	1

In the top layer (2-7 cm) the value obtained for the bare kept plot is the lowest. Values for the plots with incorporated sorghum and sunflower are the highest. Results for this top layer are negatively correlated with bulk density data (Fig. 20), and thus, with total porosity. For the layer between 15 and 20 cm, there is no effect of the treatments. Only the plot sown with crotalaria shows quite a high value, possibly due to the root system and ability of this crop to increase porosity of the subsoil layer through the creation of macro (bio) pores. The B horizon always shows very low values.

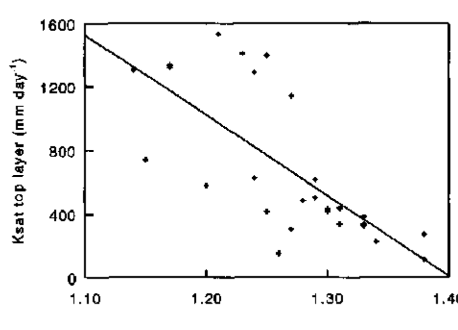


Fig. 20. *Relationship between bulk density of the top layer and K_{sat} for the summer green manuring experiment (r^2 = 0.51).*

Many references are found in literature showing that the physical passage of plant roots through the soil can produce changes in soil physical properties by creating openings and by mixing soil materials from different depths. Sods and perennial plants are mentioned by Bathke et al. (1992) as having a greater ameliorative effect on soils where high strength layers are present, but no reference is found specifically on the crops we are dealing with.

Infiltration rates

a) Tillage - rotation experiment

In the tillage - rotation experiment, infiltration was measured as already described in § 4.2.7, and results are shown in Fig. 21. Although not statistically significant, there is an influence of tillage systems. Vertical tillage plots maintain a positive effect on infiltration rate after some months, and reduced tillage always shows lower values, together with the plots sown with fescue. Rotation systems (not presented here) do not make any difference for this determination.

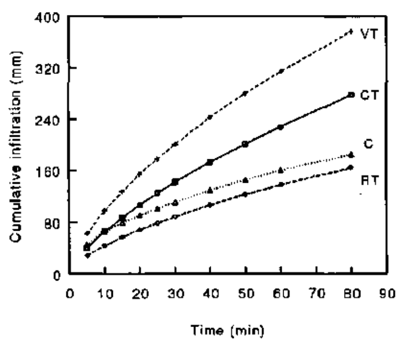


Fig. 21. *Tillage effects on infiltration. Tillage - rotation experiment. (Key to symbols: CT: Conventional Tillage; VT: Vertical Tillage; RT: Reduced Tillage; C: Fescue)*

Results obtained by Allmaras et al. (1977) working in a dry area in USA on a deep silt loam profile, show that chiselling improves water relations and thus infiltration rates in the upper 30 cm of a layered soil. Derpsch et al. (1991), working in a Latossolo Roxo in Paraná, Brazil, report intermediate values for infiltration rates when tillage is performed with chisels in comparison with conventional tillage (giving the lowest values) and with direct sowing (the highest). They associate the good results with higher surface roughness (rugosity) and higher porosity.

In our research, the infiltration rates found under VT, in accordance with Derpsch et al. (1991), can be related to a higher mean weight diameter of aggregates in the seedbed (§ 5.1.2) when compared to CT. Although conditions in the seedbed are better under RT immediately after the seedbed is prepared (Fig. 8), in the subsurface layer this tillage system shows a lower porosity (Fig. 10) when compared to VT. This is possibly due to the characteristics of the offset disc harrow, the main implement used in the RT treatment. It is a heavy implement, with a good loosening effect of the top layer. It can however, seriously compact the subsurface layer. In this experiment we could not see a positive effect of a four year pasture (fescue) on the rate of infiltration. This observation is supported by Chan and Mead (1989). They found that a 25-year old permanent pasture had the highest density of macropores and % of transmitting macropores, while a 9-year old pasture phase in a pasture/crop rotation did not fully restore the macroporosity of the soil.

b) Green manuring experiments

Infiltration was determined for the summer and the winter green manuring experiments by means of the Kamphorst simulator. Results can be read from table 15 as a percentage of total rainfall (100-% runoff). There is a positive influence of green manure incorporation on the amount of water infiltrated in the two experiments (Fig. 22).

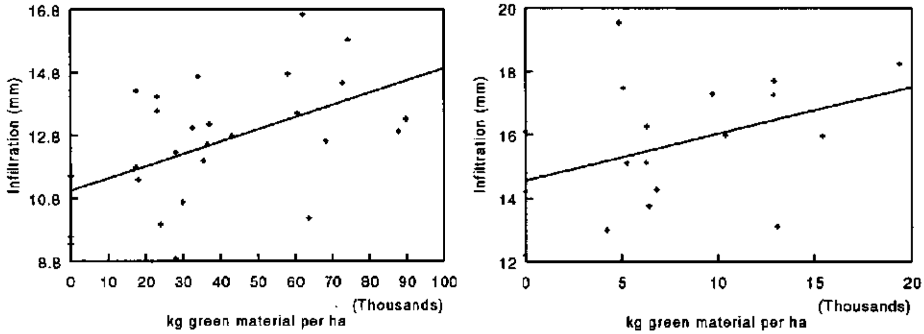


Fig. 22. Relationship between amount of green material incorporated and infiltration values measured with the Kamphorst rainfall simulator. Left: summer green manuring experiment (r^2 = 0.26, p = 0.01). Right: winter green manuring experiment (r^2 = 0.16, p = 0.10).

In the summer green manuring experiment sorghum and sunflower show higher values for infiltration. In the winter green manuring experiment, infiltration values for serradela and alfalfa are the highest. In both cases, the plots showing higher infiltration amounts show as well lower absolute sediment losses. Short term effects are then evident.

Moisture retention curves

In this research, the pF curve was determined on samples from several treatments in the tillage - rotation experiment. It was done for the upper layer of the B horizon based on the fact that this layer could be the most worsely affected by a combination of traffic and of tillage implements working repeatedly at a depth of 15 to 20 cm depth. Fig. 23 shows an averaged pF curve over treatments.

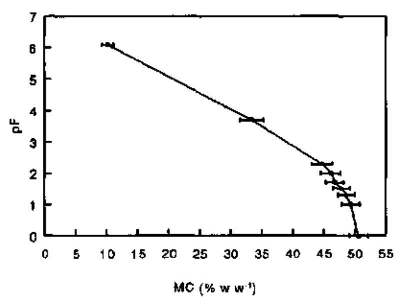


Fig.23. Moisture contents at several pF values corresponding to the B horizon (upper layer) of the tillage - rotation experiment.

Already in 1961, Kuipers described the relationship between moisture content at pF 2 and pore space, depending on texture and/or on compaction. He found that the moisture content at pF 2 is an indicator for status of structure, showing higher values when the total pore space is higher. Voorhees and Lindstrom (1984), for a silty clay loam in Minnesota, report that 3 to 4 years are required before continuous conservation tillage has a more favourable porosity in the top 15 cm layer than continuous ploughing. For the duration of our experiments, it is not possible to see any difference in the pF curves due to effects of tillage systems.

Surface crusting

The sealing index described under § 4.2.7 is used to characterize rainfall induced soil sealing by determining to what extent the permeability for water of a saturated soil sample is restricted by a rainfall developed seal or crust compared to that of an original, untreated soil sample. This was determined for the winter green manuring experiment and results are shown in Fig. 24.

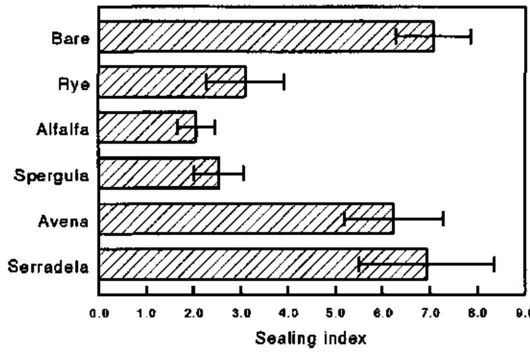


***Fig. 24.** Sealing index for the winter green manuring experiment.*

As variations in the results are very high, a special procedure was followed for the analysis of the data. Once the saturated hydraulic conductivity was measured for each sample, the averages were calculated for the sealed and the unsealed samples. It was observed that the average values were influenced by, sometimes a few, very extreme values caused by samples with large holes or cracks. Plotting the values for the saturated hydraulic conductivity gave a logarithmic-normal distribution which is confirmed by Black (1986). It was therefore decided to exclude the most extreme values on both the higher and the lower range (outliers in the 5% interval). After this procedure was followed, the standard deviations for the six treatments varied from 0.78 to 2.94.

The practical problems that arose when determining the K_{sat} were due to the fact that the samples were taken in very loose, recently tilled soil and in a layer with much (buried) crop residues and/or weeds. In some occasions the soil was also very dry. Therefore, big pores and cracks were at times present, causing the extreme values of the K_{sat}. Samples were also settling, sometimes up to 15% of the original sample height. To prevent this effect, the measurement was done as soon as a first equilibrium flow was observed.

A summary of the results is presented in Table 17. The highest values of the index were found in all cases for the bare kept plots and the lowest for those with buried alfalfa. Plots under avena negra show high sealing index, together with high amounts of runoff but low soil losses, while bare kept plots show high sealing index, high runoff and high losses. Results for the plots under alfalfa show a low sealing index, consistently related to low runoff and low sediment losses, as well as to high structure stability parameters (wet sieving diameter). Correlation coefficients with wet sieving diameter, organic matter content, runoff %, and total sediment losses obtained with the Kamphorst rainfall simulator are all below 0.35 (r^2<0.12).

Table 17

Summary of results obtained in the winter green manuring experiment in relation to the sealing index. (Latin names of crops in Table 15)

Treatment		Sealing index	Runoff %	Soil losses tons ha^{-1}	Green material tons ha^{-1}	WSD mm
1	bare kept plots	7.1	28	1.5	0	0.99
2	Rye	3.1	24	0.7	6.2	1.08
3	Alfalfa	2.1	15	0.3	4.7	1.84
4	Spergula	2.5	19	0.8	7.7	1.04
5	Avena negra	6.2	21	0.4	13.8	1.34
6	Serradela	6.9	9	0.2	14.0	1.36

A failure could be assumed in the determination of the index for serradela and avena negra, due to the problems already discussed. This is supported by the fact that when the analyses are performed leaving aside the values for serradela and avena negra, there is a tendency for the sealing index to be higher in the plots where values for runoff and soil losses are higher. In this case, the positive effect of the incorporation of green manure is evident as well.

The positive effect of vegetative cover and mulching (protecting the surface of the soil) with respect to crust formation is widely mentioned in literature (Hoogmoed, 1994). Baumhardt et al. (1992) studied the effect of chisel and disc tillage on a clay loam soil in Texas and found that chiseling had little effect on infiltration when crusts are developed. Crusts and seals due to raindrop impact decreased infiltration and eliminated the effect of chisel tillage, thus illustrating the importance of crop canopy or residue cover to prevent crust formation. Because of agreement in literature about the effect of residues, and the tendencies found in our research, the methodology is thought to be valid. However, conditions more standardized than those that we could obtain, are still needed.

5.2 Results under laboratory controlled conditions

A range of structural status was prepared in the laboratory. In a first step we present the indicators of the differences achieved in the structure conditions. In a second step, we explain the procedure to define two moisture limits within the prepared range of structure. As a last step we present the behaviour of samples of different structural conditions after simulated rainfall. That behaviour is analyzed by measuring splash, runoff and crust formation.

5.2.1 Preparation of an artificial range of structural status

Compaction of pre-moistened aggregates

Soil material was collected from the three sites where the experiments were carried out. Both A and B horizons were sampled in May 1995. On these sites, different management had been applied. For site 1 (tillage - rotation experiment), a general seedbed preparation was performed in 1994. On site 2 (summer green manuring experiment), a mixed pasture was installed immediately after our last sampling was finished. Site 3 (winter green manuring experiment) was left fallow and covered with weeds.

Since a range of moisture content around pF 2 was defined, we determined that value. Once the range was prepared, the aggregates were compressed up to a maximum pressure of 4 bar (0.4 MPa). The press being used (§ 4.2.8) gives continuous output to a computer on forces and displacement, enabling the graphing of the ongoing changes.

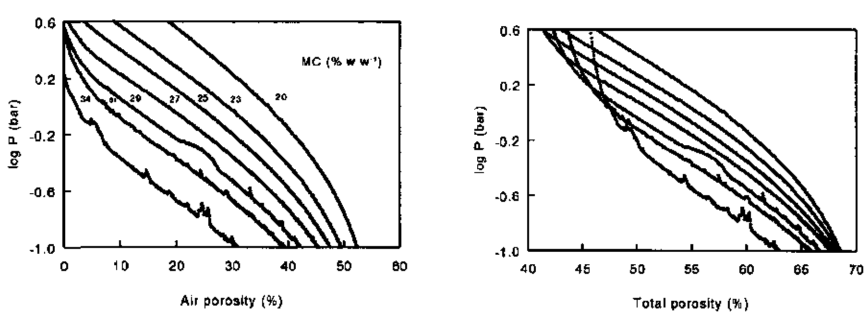


Fig. 25. *Pressure - porosity curves for various moisture levels to a maximum of 4 bar. For the A horizon of site 1. (N.B. log 4 = 0.6).*

Results for the A horizon in site 1 are presented as an example in Fig. 25. Results for all sites (A and B horizons) are presented in Appendix V (a and b). At constant levels of pressure, the graphs show the decrease in total porosity (right) and in air filled porosity (left) with increasing moisture contents. For a given moisture content, total and air filled porosity decrease at increased compression. Air porosity becomes apparently negative on the wet side of the curve, with water escaping from the sample.

Artificial range of structure

The moistened and compacted samples were allowed to air dry and aggregates (between 4.8 and 8 mm diameter) were obtained by gently crushing them. The determinations performed with those aggregates are described under § 4.2.8. Figures 26 to 28 are composite diagrams showing several of the results, all of them expressed as a function of the soil moisture content at compaction. In this way results can be interrelated. Graphs *a* and *b* represent the results obtained with the rainfall simulator. Graph *c* shows results of the wet sieving analyses, and graph *d* shows the M-P-V diagram (introduced in § 4.2.8).

We start with the discussion of graphs *d* and *c* since they show the range of structure conditions achieved. The given load for the M-P-V curve in this case is 4 bar. This curve consists of two parts, a descending curve at the left called the dry limb and an ascending one at the right, called the wet limb. Lerink (1994) states that compaction exerted in the dry limb is associated with strength hardening, and compaction exerted in the wet limb with flow. He found that the uni-axial compaction test approximates the true process of traffic-induced compaction in the field, but the degree of similarity decreased at higher water contents at compaction. The aggregate size distribution obtained after a wet sieving analysis (WSD in graphs *c*) was chosen as an indicator of structure condition that could be used to compare these results with those previously obtained in the field and in the laboratory with natural aggregates. It is clear that within the range of moisture contents corresponding to the dry limb of the M-P-V diagram, the stability of aggregates decreases when the moisture content at compaction increases. Once in the wet limb of the curve, the values for the WSD increase, especially in the B horizons. The strength of aggregates in these clayey B horizons is higher, and when there is too much water under confined conditions, they keep their status, not being damaged by compression.

This may not be the case in the field, when compression under wet conditions is causing flow and further structural deterioration may occur. Processes occurring under wet field conditions are explained by Kooistra and Tovey (1994). Collapse occurs during which the fine clay particles flow and are squeezed between larger sand and silt particles, causing the formation of orientated coatings around these grains.

Extra care was taken in the above described procedure to keep up the degree of standardization for sample preparation and measurements, in order to minimize the disturbance due to experimental set-up. The M-P-V curves (graphs *d*) were smoothed and they are presented together with the saturation line. According to Lerink (1994), as these M-P-V diagrams are defined for a set of soil characteristics (defined horizon of a defined profile) and go through a well standardized laboratory procedure, they can be considered prediction curves. For the other measurements (graphs *a*, *b* and *c*) the lines are not smoothed. The amount of soil material was limited and thus each method was applied only one time. There were also more possible sources of variations, as in the case of the wet sieving analysis for which the aggregates were hand made, sieved and kept in plastic bags until the method was performed. In view of that, it was decided to present the result of each individual measurement. Except for the B horizon from site 2 (where the amount of soil was not enough), both the dry and the wet limbs of the curves were obtained within the prepared moisture range. Our discussion is based on results for A horizons. Nevertheless, results for B horizons are shown to stress the consistency of the effects.

The moisture content at pF 2 measured on natural aggregates is shown in the graphs. This value was again measured on the artificially prepared aggregates and complete data are presented in Appendix V c. It is as well an indicator for changes achieved by compaction in the structure of the samples. For the A horizons in the three sites, the moisture content at pF 2 increases when compaction is done under increasing moisture contents, due to an increase in the total pore space (Kuipers, 1961). For the B horizons the moisture content at pF 2, determined in the aggregates obtained after the compacting procedure, is always lower than the value obtained for natural aggregates. This lowering of values can be an indication of severe compaction, referred as well by the mentioned author. This severe compaction can result in denser aggregates.

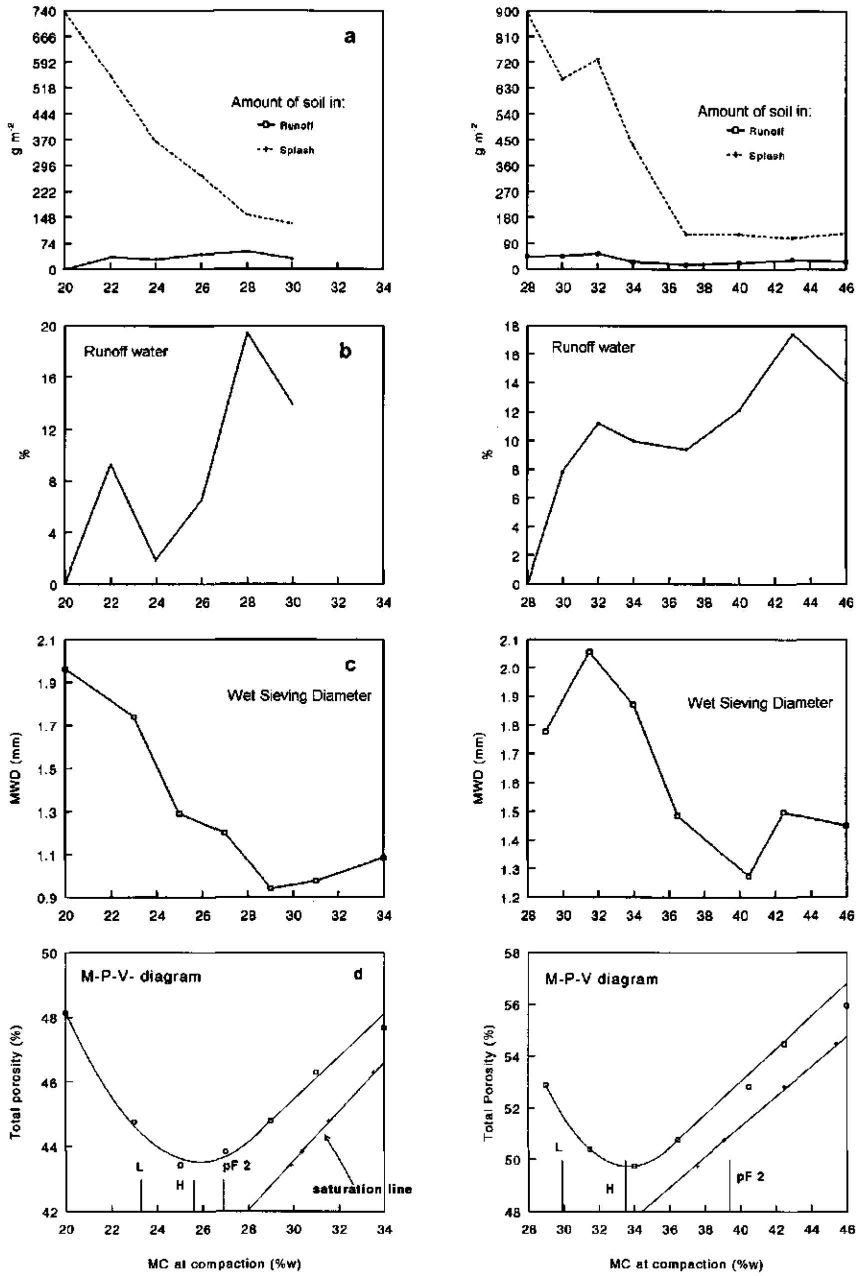


***Fig. 26.** Effects on splash (a), runoff (b), wet sieving diameter (c) and total prorosity (d) of a pressure of 4 bar under various moisture contents. Site 1 (left: A hor, right: B hor). L and H: low and high limits of structure conditions.*

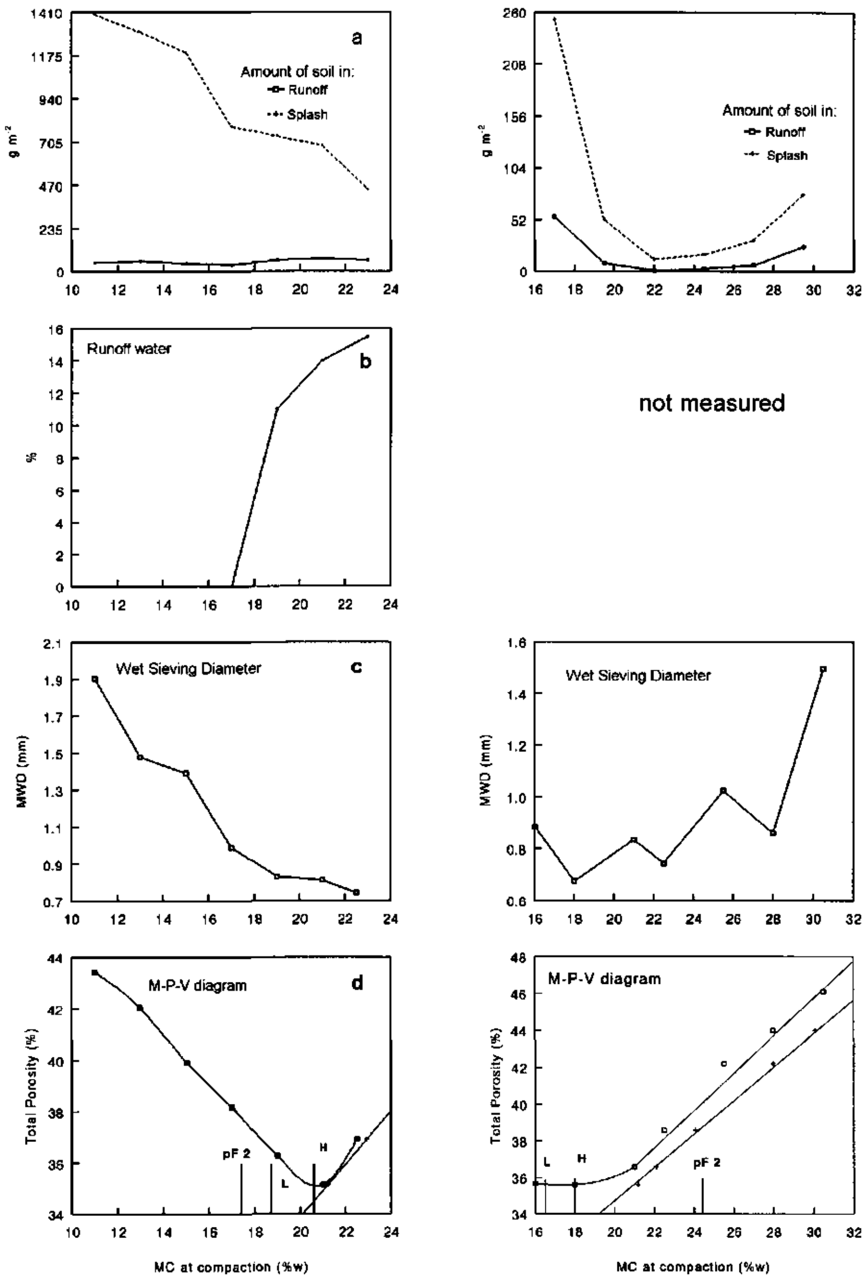


Fig. 27. *Effects on splash (a), runoff (b), wet sieving diameter (c) and total porosity (d) of a pressure of 4 bar under various moisture contents. Site 2 (left: A hor, right: B hor). L and H: low and high limits of structure conditions.*

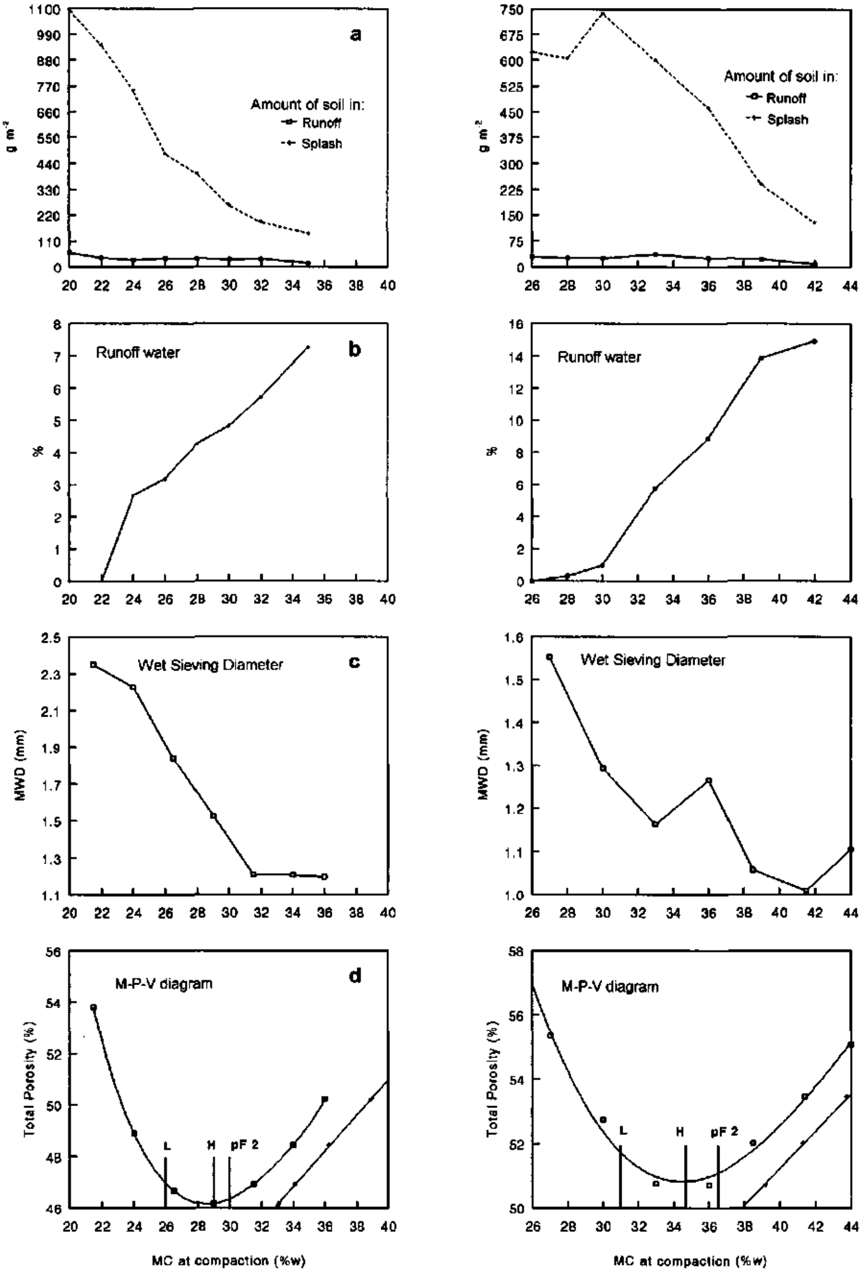


__Fig. 28.__ Effects on splash (a), runoff (b), wet sieving diameter (c) and total porosity (d) of a pressure of 4 bar under various moisture contents. Site 3 (left: A hor, right: B hor). L and H: low and high limits of structure conditions.

5.2.2 Definition of two limits within the prepared range of structure conditions

Before air drying the samples that were compacted up to a pressure of 4 bar under different moisture contents, both air permeability and saturated hydraulic conductivity were measured. Results are shown in Fig. 29 and Fig. 30 for A and B horizons of the three sites. Those corresponding to Fig. 30 will be discussed next in § 5.2.5.

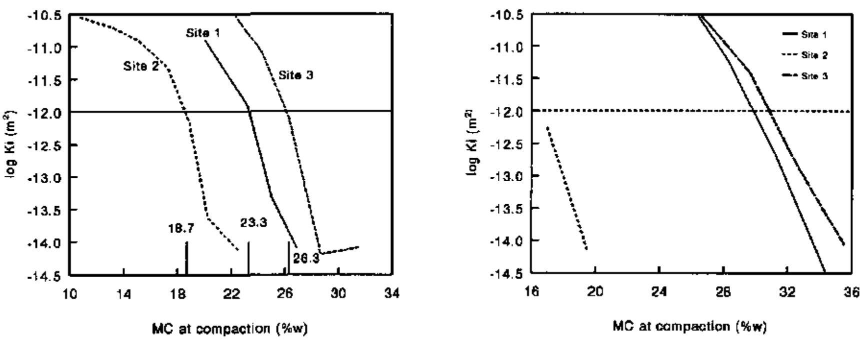


Fig. 29. *Air permeability after compaction with increasing moisture contents. Left: for A horizons. Right: for B horizons.*

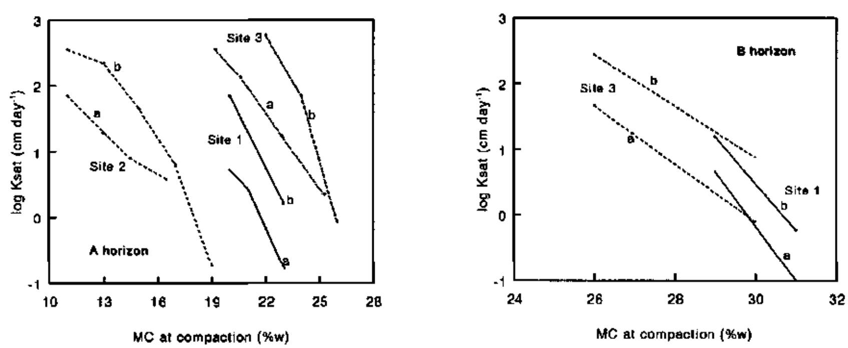


Fig. 30. *Saturated hydraulic conductivity after compaction with increasing moisture contents. a: after rainfall simulation. b: before rainfall simulation.*

Based on the results of the determination of air permeability (Fig. 29) and on the M-P-V diagram (Figures 26 to 28), three ranges of soil moisture contents in the arable layers (A horizons) are chosen for further discussion. The lower range is defined as the one from dry conditions up to the moisture content where log K_i has a value of -12 m^2 (indicated with a line in Fig. 29 and with L in Figures 26 to 28). This limit has been defined by Perdok and Hendrikse (1982) as the wet workability limit. The second moisture range is from L up to the level where the M-P-V diagram has its lowest value (H in Figures 26 to 28), indicating a critical water content resulting in maximum compaction (thus minimum porosity). The third range corresponds with the wet limb of the M-P-V diagram. Values obtained in the two lower ranges of moisture contents (< L and L - H) could be expected under field conditions. Results obtained under artificial laboratory conditions with moisture contents higher than level H cannot be expected under field conditions. In the field, compression with moisture content higher than H will cause flow.

5.2.3 Range of values for the selected indicator of structure status: WSD

Ranges obtained for the wet sieving diameter under field and laboratory conditions are presented for each site in Table 18. For site 2, only two ranges can be defined under laboratory conditions, because values for the wet sieving analysis obtained between L and H are not varying, due to the sandy characteristics of this site.

Table 18

Values obtained for wet sieving diameter (WSD in mm) with natural (taken from the field) and with laboratory prepared aggregates. (Key to symbols: < L: moisture contents at compaction below L; H - L: moisture contents at compaction between L and H; > H: moisture contents at compaction above H)

	Natural aggregates		*Artificial aggregates*		
	Minimum	*Maximum*	*> H*	*H - L*	*< L*
Site 1	2.63	3.97	< 1.25	1.25 - 1.70	> 1.70
Site 2	0.54	1.06		< 0.85	> 0.85
Site 3	0.99	1.84	< 1.50	1.50 - 1.90	> 1.90

While for sites 2 and 3 the values fall within similar ranges, either when samples are taken from the field or prepared in the laboratory, this is not the case for site 1. The wet sieving analysis for site 1 with field samples was performed almost one year after the samples were collected and air-dried, while for sites 2 and 3 it was performed immediately after the sampling. The ageing of aggregates (Dexter, 1991) can provide an explanation for the observed differences. Considering data obtained for sites 2 and 3, the method shows to be useful to describe changes in structure conditions in the field, even after short term management differences.

For sites 1 and 3, the graphs show that when the moisture content at compaction is between L and H, the values obtained for the wet sieving diameter decrease consistently. Under field conditions, when the values for the wet sieving diameter fall within this range, it could be considered an indication that structure status needs improvement. For site 2 (sandy soil) the wet sieving diameter falls down to its lowest values already in the dry range. Structure in this soil type is weaker and more seriously affected by compaction.

From the values obtained, it is then possible to define ranges for the wet sieving diameter to be used as indicator of structural status for each soil type. In § 5.2.4 we will describe the meaning of the ranges for the wet sieving diameter on the behaviour of the soils with respect to rainfall erosion.

5.2.4 Effects of structural status on losses by simulated rainfall

Results obtained with the rainfall simulator are presented in Figures 26 to 28. Graph *a* shows the amounts of soil lost with splash and with the runoff water. Graph *b* shows the total amounts of runoff water. Table 19 presents a summary of the data obtained for the A horizons (complete data are presented in Appendix V d).

When compaction is performed under increasing moisture contents, the amount of particles detached by splash is consistently lower, runoff increases and the amount of soil lost in the runoff water is not changing within the range and under the conditions of this experiment. The samples were placed under the rainfall simulator on a horizontal plane, not simulating any slope. The total amount of runoff cannot be known since part of it went into the splashed water. Because of the set up of the experiment, it was not possible to derive how much of the splashed water would end up as runoff or would infiltrate into the soil. When a comparison is done with the indicator of structural stability (WSD), the amount of particles detached by rainfall splash decreases consistently with the decrease of the diameter.

Table 19
Runoff and soil loss from soil samples from A horizons under laboratory rainfall simulation (L and H: see Figures 26 to 28)

Site	*MC (% w w^{-1}) at compaction*		*Splash (g m^{-2})*	*Runoff (% of rainfall)*	*Soil in runoff (g m^{-2})*
1	20		736	0	0
	22		554	9	34
	23.3	**L**	430		
	24		365	2	28
	25.4	**H**	295		
	26		267	7	42
	28		157	19	50
	30		131	14	30
2	11		1401	0	49
	13		1304	0	57
	15		1195	0	43
	17		791	0	35
	18.7	**L**	750		
	19		738	11	62
	21		688	14	68
	23		448	15	61
3	20		1096	0	61
	22		944	0	38
	24		752	3	30
	26		482	3	35
	26.3	**L**	480		
	28		397	4	35
	29	**H**	340		
	30		263	5	31
	32		190	6	33
	35		142	7	16

Our results are in agreement with those reported by Bollinne (1978) who worked in Central Belgium on a silty eroded soil. He presents data obtained under field and laboratory conditions, where he found that splash is directly related to the structural stability of the soils. This is also explained by Mazurak et al. (1975) by the easier detachment of stable aggregates by raindrops, the lower strength of the crust and the lower density of the most stable soils.

Results in our experiment show the same trend as described by Nishimura and Nakano (1990). When working with a clayey loam soil sieved to 3 mm, they observed the development of a crust of 3 mm thickness after the performance of rain simulation with similar characteristics as ours. Saturated hydraulic conductivity decreased by a factor of 250. Runoff started after 20 minutes of rain, and increased with time. A steady state was reached in which 90% of rain drained away by runoff and 10% infiltrated. Soil losses by splash decreased as rainfall was repeated many times, independently of slope. Thus, crust formation strengthened the soil surface. They worked with several slopes and state that when slope angle increases, runoff erosion becomes higher. Concentration of eroded material in runoff water decreased gradually in the first run of the rain and it remained unchanged in the second run to follow. As the inclination of the slope increased, the concentration of the runoff water became high. That indicates that under slopy conditions, crust formation would not prevent soil materials to be lost with the runoff water.

It is clear from our results that when a range of structure status is created by compacting samples under different moisture contents, the lower the structure conditions (lower WSD), the lower the amount of soil lost with splash and the higher the amount of runoff water. Although the total amount of soil lost with the runoff water is not known, it is possible that it increases when structure becomes worse, according to results obtained by Nishimura and Nakano (1990) already described.

Values for splash under laboratory conditions are ranged following the same procedure as for the WSD, and presented in Table 20.

Table 20

Ranges defined for amount of splash obtained in g m^{-2} under laboratory conditions for A horizons of the three sites

	> H	*H - L*	< *L*
Site 1	< 295	295 - 430	> 430
Site 2		< 750	> 750
Site 3	< 340	340 - 480	> 480

Three ranges are defined for amounts of splash obtained under the different moisture contents at compaction. The amounts corresponding to the two limits used to define the ranges (L and H) were calculated by a curve fit (non-linear interpolation) computer procedure from the data in Table 19. It is not possible to compare these values with those obtained under field conditions (§ 5.1.4), since methodologies are different. For site 1, the tendencies in the field and in the laboratory coincide, showing higher amounts of splash when the wet sieving diameter is higher. The effect of a crust being formed here is evident. This will be further related to the determination of the sealing index under laboratory conditions. For site 2 the tendency is not the same as for site 1 since the amount of splash under field conditions is now highest with the lowest wet sieving diameter value. In site 2 then, under field conditions the effect of incorporating crop residues that act as a mulch on top of the soil is more evident. The sowing of the barley was done a short time after the mixing of crop residues. These residues act as barriers for rain drops, thus resulting in lower detachment. In site 1 the period of time between the incorporation of residues and the sowing was longer, so the effect of structure status can be directly reflected on the crust development. When data from the field and the laboratory are compared, two effects are evident due to residue incorporation. One increasing the stability of structure, and the other acting as a physical barrier for raindrops.

With respect to amounts of runoff and infiltration under laboratory conditions, data show an increase in runoff rates (Figures 26 to 28 *b*) when the wet sieving diameter decreases. It is not possible to know the total amount of soil lost by runoff with this experiment, but it is likely that the increase in runoff will cause an increase in total soil losses. This was evaluated under field conditions for sites 2 and 3 (Table 15). As a tendency, it is also true that the higher the wet sieving diameter, the lower the runoff losses.

5.2.5 Sealing index (SI)

Saturated conductivity is determined before and after the rainfall simulation to calculate the sealing index. Results are presented in Table 21 (values for K_{sat} are shown in Fig. 30). From these data, it can be seen that with increasing moisture contents at compaction, there is a decrease in the sealing index. This means that the decrease in saturated conductivity is lower when the structure status becomes worse. In the drier ranges of compaction, it is possible to see that the three sites are different with respect to risk of crust formation, being highest for site 3 and lowest for site 2 (highest and lowest SI respectively).

Table 21
Results of the sealing index (SI) for samples prepared under laboratory conditions, soil from the A horizons of the three sites

Site	MC (%w) at compaction	SI
1	20	13
	23	10
2	11	4
	13	11
	15	8
	17	4
	19	1
	20	3
3	22	19
	24	14
	26	1

A comparison between these data with those obtained under field conditions (Fig. 24) is not possible. For the simulation in the laboratory the samples were kept with the moisture contents given before they were compacted. When the simulation was done on samples taken from the field, these samples were taken all in the same moment and thus having a quite similar moisture content. While under field conditions the differences in structure were real, under laboratory conditions the differences were artificial. Due to this fact, in the laboratory, the higher ranges of moisture contents have a decreased water conductivity already before the rainfall simulation, due to compaction under wet conditions (lines b in Fig. 30 left). That decrease is even larger after rainfall (lines a in the same figure) but relatively lower when initial conditions are worse by having a higher moisture content at compaction (lines a and b tend to get closer to each other).

Results obtained for the sealing index explain the behaviour of the three sites with respect to crust formation, and they will be used in the next chapter to simulate rainfall redistribution depending on soil characteristics.

6 MODELLING OF WATER BEHAVIOUR ON LAYERED PROFILES

6.1 Inputs to the Model

The required inputs for the SWIM model include i) time dependent climatic inputs, ii) soil moisture characteristic, iii) saturated hydraulic conductivity (the unsaturated is calculated by the model), iv) initial and minimum soil surface conductance (K_{sat} divided by the thickness of the surface layer), v) initial and minimum surface storage (water detention) and vi) rates at which conductance and surface detention decrease with rainfall. Vegetation is not considered in our simulations, as our interest is soil behaviour according to the soil physical properties.

i) The required time dependent climatic inputs are cumulative rainfall and cumulative potential evapotranspiration. Two months of 1986 (October and November) were chosen as they are representative for a critical rainy period (525 mm total for both months), as shown in Fig. 31. Since the model can interpret real storm intensities, hour intensity data recorded in Paysandú and provided by the Meteorological Division of the Ministry of National Defense of the country were used. The cumulative rainfall over the two month period is presented in Fig. 32.

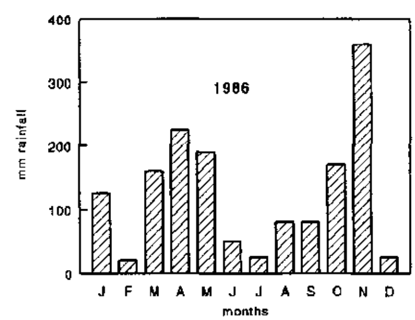


Fig. 31. Monthly rainfall distribution in Uruguay for 1986 in mm.

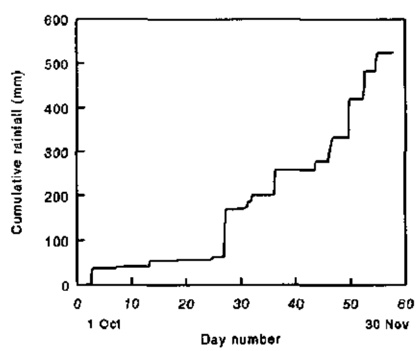


Fig. 32. Cumulative rainfall in October-November 1986.

The potential evaporation was taken as a monthly means from Schwerdtfeger (1976), 97.4 mm for October and 129.8 for November (over a year, minimum is 53.5 for June and maximum is 161 for December). The total period of simulation was 58 days.

ii) The parameters related to the soil moisture characteristic required by the model are the moisture content at saturation (θ_s in % v v^{-1}), the air-entry potential (ψ_e in cm) and the slope of a straight line approximating the water retention curve on a log-log plot. The ψ_e may range from -1 cm in sandy soils to -50 in clays, and the slope can range from -2 in sandy soils to -25 in clays (Ross, 1990 a). For our simulation we obtained these values according to Hutson and Cass (1987), selecting soils that closely resembled our sites in terms of clay content, silt/clay ratio and bulk density. In Table 22 a summary of these values is shown. For site 1, the values obtained this way are quite similar to the pF curve values obtained by our laboratory determinations. In view of that we assumed that the same procedure could be followed as well for sites 2 and 3. For both sites, the results were compared with pF curve values obtained by Terzaghi et al. (1988) working with other soils in Uruguay, some of them having characteristics similar to these. They are considered in fact, good approximations.

Table 22

*Values of soil properties of three sites in Uruguay, used as inputs for the SWIM model (Key to symbols: BD: bulk density, b: minus the slope of the retentivity curve on log-log plot, ψ_e: water entry potential, θ_s: total porosity and K_{sat}: saturated hydraulic conductivity. Source: *Hutson and Cass, 1987; + measured)*

Site	Horizon	BD(+) (g cm^{-3})	b(*) (cm)	ψ_e(*) (% v v^{-1})	θs(+)	K_{sat}(+) (mm day^{-1})	K_{sat}(+) (with crust)
1	A	1.2	8	- 5	0.456	200	15.4
1	A	1.4	12	- 8	0.391	150	
1	B	1.4	20	-10	0.419	2.4	
2	A	1.2	8	- 1	0.484	700	63.6
2	A	1.4	8	- 1	0.400	220	
2	B	1.6	13	- 5	0.353	2.4	
3	A	1.1	7	- 4	0.539	400	28.6
3	B	1.3	15	- 7	0.465	100	

iii) Saturated hydraulic conductivity for site 2 was measured on undisturbed samples, but that was not the case for the other profiles. For site 3, the values were chosen by comparison of the site characteristics with those of a standard reference list of soils in The Netherlands for which the K_{sat} was measured

(Wösten, 1987). For site 1, values are estimated according to our experience, as it was not measured and it was also not possible to find a similar type in the list already mentioned.

iv) The initial soil surface conductance is calculated according to Ross, 1990 a. The K_{sat} is divided by 0.5 cm (thickness of surface layer) to obtain this value. The model considers a reduction of surface conductance due to formation of a crust caused by rainfall. That reduction is exponentially related with cumulative precipitation energy, from the given initial value towards the given minimum. The minimum surface conductance in our simulations was obtained reducing the initial value with a factor that expressed the reduction obtained for K_{sat} in the laboratory after simulation of rainfall on pre-compacted aggregates (last column in Table 22).

v) For initial and minimum surface storage (or water detention) expressed in mm, we used data reported in literature for comparable soils. These values were obtained by Mwendera and Feyen (1992) for a silt loam soil in Belgium under laboratory conditions, and by Römkens and Wang (1987) for a fine silty soil in USA. They are shown in Table 23, and should be considered approximations.

Table 23

Values of initial and minimum surface storage (mm) used as inputs for the model (Source: Mwendera and Feyen, 1992; Römkens and Wang, 1987)

Initial surface storage:	disc or chisel plough	50
	VT or RT	35
	CT	30
Minimum surface storage:	VT or RT	18
	CT	9

The value 50 mm expresses a reference optimal condition of surface roughness. The value 35 mm is reported in the literature mentioned above as the surface storage in the seedbed when a tillage system similar to our reduced tillage (RT) is used. Therefore we chose 35 mm as the initial value for vertical and reduced tillage. The relative difference obtained in our research for mean weight diameters in the seedbed when comparing reduced or vertical tillage systems with conventional tillage (16 and 13.9 mm respectively, shown in

Fig. 8) is used to choose the initial surface storage under CT (30 mm). For the final (minimum) values, we use those obtained by the abovementioned authors (18 and 9 respectively).
Runoff occurs when the surface water depth is greater than the surface storage. To allow for a reduction of surface roughness due to rainfall, the storage decreases exponentially with precipitation energy from the given initial value towards the given minimum in the same way as the surface conductance.

vi) The rates at which conductance and surface detention decrease with rainfall depend on precipitation intensity. We used the values presented by Ross (1990 a) for an intensity of 25 mm h^{-1}. Both conductance and surface storage fall 63% of the total decrease, after the given precipitation constant (25 mm) assuming that the precipitation falls at 25 mm h^{-1}.

For the three sites, the depth of the profiles was considered to be 60 cm. For sites 1 and 2 the A horizons were divided in two layers, as this is the actual situation. For each of the three sites, the top 1 cm was divided in three layers of 0.2, 0.3 and 0.5 cm, in order to be able to simulate crust formation. The rest of the profile was divided in layers of 2.5 cm thickness. In Appendix VIa the complete input data for the three sites are shown. There was no watertable influence on profile hydrology. The initial soil water content was set at field capacity throughout the soil profile.

6.2 Modelling results and discussion

A summary of the results of the simulations for the three sites is presented in Table 24. The runoff and infiltration are shown as a percentage of total rainfall. A description of the various conditions that were simulated, follows in this chapter.

6.2.1 Tillage systems and structure conditions

Tillage systems and structure conditions were simulated by changing the surface storage capacity (cases *a*, *b* and *c* in Table 24). Values for surface storage were used as explained earlier in this chapter (Table 23). With respect to structure status, a soil with low structural stability will suffer a higher reduction in surface detention with increasing rainfall energy, being therefore more likely to produce runoff for a given rainfall regime. As surface detention was not measured in our research, values in case *b* of table 24 are estimated as occurring under relatively good structure conditions, and values in case *c*, under worse conditions.

Table 24

A) Runoff (%RO) and infiltration (%I) as percentage of total rainfall when the simulation is performed for different soil conditions for the three sites

		Site 1		*Site 2*		*Site 3*	
Case	*Conditions*	*%RO*	*%I*	*%RO*	*%I*	*%RO*	*%I*
a.	High surface storage	34	66	32	62	0	100
b.	Medium surface storage	40	60	39	61	0	100
c.	Low surface storage	43	57	41	59	0	100
d.	Low BD A hor	40	60	38	62	0	100
e.	High BD A hor	41	59	42	58	2	98
f.	Crusted	42	58	41	59	11	89
g.	No B horizon, no crust	3	97	1	99	0	100
h.	No B horizon, crusted	21	79	9	91	11	89
i.	Eroded profile	43	57	43	57	2	98
j.	Eroded profile, crusted	45	55	44	56	11	89

B) Key to cases in Table 24 A (SSi: initial surface storage, *SSf:* minimum (final) surface storage)

	Sequence of horizons	*SSi (mm)*	*SSf (mm)*	*BD (g cm^{-3}) A horizon*		*Crust*	*Eroded profile*
				0-15 cm	*15-30 cm*		
Case a.	A - B	50	50	1.2	1.4	No	No
Case b.	A - B	35	18	1.2	1.4	No	No
Case c..	A - B	30	9	1.2	1.4	No	No
Case d.	A - B	35	18	1.2	1.2	No	No
Case e.	A - B	35	18	1.4	1.4	No	No
Case f.	A - B	35	18	1.2	1.4	Yes	No
Case g.	A	35	18	1.2	1.4	No	No
Case h.	A	35	18	1.2	1.4	Yes	No
Case i.	A - B	35	18	1.4	1.4	No	Yes
Case j.	A - B	35	18	1.4	1.4	Yes	Yes

Another potentially variable condition simulated was the bulk density of the A horizons. This is treated in cases *d* and *e*, in *d* with a bulk density of 1.2 g cm^{-3}

in the two layers of the A horizon and in *e* with a value of 1.4 g cm^{-3}. Although for site 3 this is not relevant since actual conditions in this site are not changing with depth for the A horizon, results of simulations are also shown. In sites 1 and 2 the A horizon is actually varying with depth to more compacted conditions.

A serious reduction in surface storage (case *a* vs *c*) causes the runoff percentage to increase from 34 to 43% in site 1 and from 32 to 41% in site 2. For site 3 there is no runoff in any storage condition. An increase in bulk density (case *d* vs *e*) leads to small increases in runoff (at site 1 from 40 to 41%, at site 2 from 38 to 42% and from 0 to 2% at site 3).

6.2.2 The relevance of the B horizon

To study the relevance of the B horizon in water movement through the soil, results from the simulation under the sequence of horizons as found in the field (case *b*) were compared to those obtained assuming that the whole profile had the characteristics of the A horizon (case *g*). For sites 1 and 2 the presence of the B horizon shows to be the factor limiting the water movement deeper into the profile. The amount of runoff is drastically lower when the B is not present. Hydraulic characteristics of the B horizon for site 3 are better than for sites 1 and 2 (Table 22) and the presence of that layer is not causing runoff. Although not all data for sites 2 and 3 were measured directly, the results of the simulations are a good reflection of the actual situation, according to our knowledge of the sites.

6.2.3 Surface crusting

The development of a crust is simulated and the results are shown as case *f* in Table 24. The surface crusting is simulated by reducing the value of K_{sat} of the top 5 mm layer and by further reduction of the conductance with cumulative rainfall energy. If a comparison is made with case *a*, the amount of runoff due to these conditions increases from 34 to 42% at site 1 and from 32 to 41% at site 2. For site 3 the runoff increases from 0 to 11%. The influence of a crust becomes more evident when the absence of the B horizon is simulated (cases *g* and *h*), with a larger effect for sites 1 and 3. The top soil of site 2 due to its sandy texture is always keeping higher values for K_{sat}. These results stress the influence of the B horizon for site 2, as the restricting layer for water movement through the profile, compared to the effects of surface crusting.

6.2.4 An eroded profile

In order to simulate an already eroded profile, the depth of the A horizon was reduced by 10 cm (cases *i* and *j*). When results under *e* (simulating behaviour of a soil in bad structural conditions) and under *i* are compared, the percent of runoff increases from 41 to 43 for site 1 and from 42 to 43 for site 2 . In site 3 there is no change.

6.3 Conclusions of modelling

- Results of simulations show the large effect of the B horizon preventing water to infiltrate in the profile. This is the case for sites 1 and 2, where the absence of a B horizon reduces runoff percentage from 40 to 3 and from 39 to 1, respectively. For site 3, the characteristics of the B horizon are such that this layer does not limit infiltration.

- Development of crusts as well as a decrease in soil surface storage, have varying relevance depending on the soil under consideration. For sites 1 and 2, the change in surface storage conditions from case *a* to case *c* shows an increase in runoff from 34% to 43% and from 32% to 41% respectively. There is no change in site 3. The usually lower rates of infiltration for sites 1 and 2, become even lower when tillage intensity is higher and/or when structural conditions of the surface layer are worse. The relevance of crust formation can be seen for the three sites when comparing cases *g* and *h*. Site 1 is the most seriously affected, followed by site 3. The characteristics of the top layer of site 2 indicate a lower risk for crust formation.

7 ASSESSMENT OF SOIL QUALITY IN RELATION TO RISK OF EROSION

7.1 Background

Concern has grown about how various soil and crop management practices are affecting soil erosion, together with other environmental problems. The concept of soil quality has been suggested by several authors as a tool for assessing long-term sustainability of agricultural practices (Papendick and Parr, 1992; Karlen and Stott, 1994). To assess soil quality relative to its ability to resist erosion by water, Karlen and Stott (1994) define the critical soil functions. These are to accommodate water entry, to facilitate water transfer and absorption, to resist degradation and to sustain plant growth. Within our research, we studied several possible physical indicators of those functions, pointing to the use of non sophisticated field and laboratory methodologies, that could give a good level of information. With the appropriate interpretation of the outcome of these methodologies one may be able to predict soil behaviour under varying management systems.

Based on the results obtained in our study, we propose a method of assessment of quality for the three soils under consideration. This assessment is presented schematically in Tables 25 to 27 for sites 1, 2 and 3 respectively. It is done according to methods accepted and applied in Land Evaluation to obtain tables of conversion (FAO, 1976), and adapted to our aims. A set of quantifiable soil physical properties (characteristics) is selected. Some data, such as the presence of a B horizon and the depth of the A horizon, are obtained in the field, and others are measured in the laboratory. With respect to the latter we selected those that allow a standardization and that give information that can be related to data collected under actual field conditions (sealing index and wet sieving diameter). Those characteristics that are considered more relevant to assess the ability to resist erosion are placed in the left side of the referred tables. The definition of the limiting values (described in § 7.2) is done considering both, some of the outputs obtained by simulating soil water balance with the model SWIM (Appendix VI b) and some of the data obtained in the laboratory.

Table 25

Assessment of soil quality for site 1 with respect to its ability to resist the impact of rainfall causing erosion (Key to symbols: WSD: wet sieving diameter, H: High quality, low risk of erosion. M: Medium quality and risk of erosion. L: Low quality, high risk of erosion)

B horizon	*Depth of A horizon (cm)*	*Sealing Index*	*WSD (mm)*	*Total Porosity (%)*	*Soil Quality*
Present (K_{sat} <12mm day^{-1})	<45	<10	>1.7	>40	**M**
				<40	**L**
			1.25 - 1.7	>55	**M**
				<55	**L**
			<1.25		**L**
		>10			**L**
	>45	<10	>1.7	>55	**H**
				40 - 55	**M**
				<40	**L**
			1.25 - 1.7	>40	**M**
				<40	**L**
			<1.25		**L**
		>10			**L**
Absent (K_{sat} >12mm day^{-1})		<10	>1.7	>40	**H**
				<40	**M**
			1.25 - 1.7	>40	**M**
				<40	**L**
			<1.25	>55	**M**
				<55	**L**
		>10			**L**

Table 26

Assessment of soil quality for site 2 with respect to its ability to resist the impact of rainfall causing erosion (Key to symbols: WSD: wet sieving diameter, H: High quality, low risk of erosion. M: Medium quality and risk of erosion. L: Low quality, high risk of erosion)

B horizon	*Depth of A horizon (cm)*	*Sealing Index*	*WSD (mm)*	*Total Porosity (%)*	*Soil Quality*
Present *(K_{sat} <12mm day^{-1})*	<45	<10	>0.85	>40	**M**
				<40	**L**
			<0.85		**L**
		>10			**L**
	>45	<10	>0.85	>55	**H**
				40 - 55	**M**
				<40	**L**
			<0.85	>40	**M**
				<40	**L**
		>10			**L**
Absent *(K_{sat} >12mm day^{-1})*		<10	>0.85	>40	**H**
				<40	**M**
			<0.85	>40	**M**
				<40	**L**
		>10			**L**

Table 27

Assessment of soil quality for site 3 with respect to its ability to resist the impact of rainfall causing erosion. (Key to symbols: WSD: wet sieving diameter, H: High quality, low risk of erosion. M: Medium quality and risk of erosion. L: Low quality, high risk of erosion)

B horizon	*Sealing Index*	*WSD (mm)*	*Total Porosity (%)*	*Soil Quality*
Present *(K_{sat}<12mm day^{-1})*	<15	>1.9	>60	**H**
			45-60	**M**
			<45	**L**
		1.5-1.9	>45	**M**
			<45	**L**
		<1.5		**L**
	>15			**L**
Absent *(K_{sat}>12mm day^{-1})*	<15	>1.9	>45	**H**
			<45	**M**
		1.5-1.9	>45	**M**
			<45	**L**
		<1.5	>60	**M**
			<60	**L**
	>15			**L**

7.2 Components of the quality index

The *argillic B horizon* appears as the main limiting factor for water movement inside the profiles, due to its hydraulic properties. Thus, it is placed in the first level for the assessment of soil quality. The value of K_{sat} = 12 mm day^{-1} is taken as a limit, as this value (or lower), when used as input to simulate soil water balance, leads to a runoff of at least 10% of the total rainfall in the three sites under study. Modifying the hydraulic properties of the B horizon, a decrease of the amounts of runoff is achieved, greater than the decrease obtained by modifying properties related to crust formation and/or to general structure deterioration. It is clear then that the presence of an argillic B is the main feature to be considered when assessing soil behaviour towards rainfall.

The second level is assigned to the *depth of the A horizon*. Different depths for the A horizon were simulated. Starting from 15 cm depth, a decrease of 10 units in the percentage of runoff was found when the depth was increased to 45 cm, for both sites 1 and 2. For site 3, since the B is not a limiting factor, this second level is not included.

The occurrence of *sealing* is the next important factor influencing the runoff. Sealing gives a stronger change in the rate of runoff than decreasing the surface storage capacity. Thus it is placed at the third level to be considered to assess the soil quality with respect to erosion. The limits for each site are chosen as those sealing index values where the % of runoff increases with 10 units compared to the same site with no B horizon and no crust formation. Although the soil in site 3 shows a higher risk of crust formation (§ 5.2.5), it was also found that a higher sealing index is needed to cause the same increase in runoff as for sites 1 and 2. Thus the limit is taken as 15 for site 3 and 10 for sites 1 and 2.

The fourth parameter in this sequence influencing the rate of runoff is the *surface storage capacity* of the soil. It is represented by means of the values obtained in the laboratory for the wet sieving diameter (WSD in Table 18), considering that the surface storage is highly related to the stability of structure.

Total porosity is proposed to be placed in the fifth and last level of these decision tables. The changes in this characteristic give the least changes in the amount of runoff water, but are still considered to have such an effect that justifies to be taken up in this scheme. The total porosity is rated according to the extreme values measured under field conditions for the three sites.

7.3 Application of the quality index

In order to assign a soil quality rating to a certain case, availability of information for all levels defined in the tables is required. It is not advisable to apply results from one soil type to another, especially where hydraulic properties are highly varying. With respect to the application of the index, when the soil quality is rated as *high*, the management has to be chosen in order to keep it in good conditions. When the soil quality is rated as *medium*, there is a need of an improvement, and this could be achieved in several ways, depending on what the limiting factor is. When the susceptibility for sealing (indicated by values of the sealing index) and/or the structural stability (indicated by values of the wet sieving diameter) are causing this medium quality, it is shown in our research that an improvement is possible by choosing a crop rotation where incorporation of crop residues is involved. When problems are mainly due to the presence of a B horizon, deep rooting crops would be needed to promote formation of biopores that improve hydraulic properties of that layer. When quality is rated as *low*, more drastic actions will be necessary. In that case, tillage (of top and subsoil) would still be advisable as an intermediate step to reach structure improvement. The relative influence of reduced tillage and crop residue incorporation are described in previous chapters.

8 CONCLUSIONS

Several management options (tillage systems, crop rotations and green manure incorporation) have been studied for three sites in Uruguay, on their effects on the ability of the soils to resist rainfall erosion. These effects were studied using various field and laboratory indicators. The major conclusions are listed below.

Tillage systems

The effects of various tillage systems were studied in one of three field experiments (site 1, a clayey profile).

Results of the aggregate structural stability measured with the *wet sieving analysis* on big aggregates (4.5 to 9.5 mm diameter) show that the wet sieving diameter is about 14% lower (thus lower aggregate stability) in any of the tillage systems (various tillage intensities) than in the reference plot sown with a perennial pasture. Every tillage system is causing about the same degree of damage to the structure, even when mainly traffic is implied (direct drilling). The *Henin index of instability* on the other hand, measured on < 2 mm diameter aggregates, is higher (more unstable condition) under a higher tillage intensity.

The *mean weight diameter of aggregates* in the seedbed is 15% bigger under vertical or reduced tillage as compared to conventional tillage. This improvement would be relevant and have a positive effect in the case of soils with high stability of aggregates, enabling them to maintain their shape after the occurrence of rainfall. In view of what we found with the wet sieving analysis, this was not the case under the conditions of this site.

Results of *bulk density* show slightly lower values in the layers below 10 cm depth when vertical tillage is considered. This is in agreement with the lower values recorded for the *resistance to penetration* in those layers. It may be concluded that the use of the chisel plough has beneficial effects in this site with very poor physical conditions as shown by a total porosity always lower than 45% already below 10 cm depth. The chisel is also showing benefits when the *rate of infiltration* is measured (double ring infiltrometer). There is a slight although not significant increase in that rate under vertical tillage, when compared to conventional tillage.

The *yields of the cereal winter crop* that followed the various tillage systems were not affected. Only in the case of direct drilling in the tillage - rotation experiment they were significantly lower. This can be due mainly to two reasons, one that the status of the soil is physically very poor and the second that the date of sowing was kept the same for all treatments, most likely resulting in too wet conditions for direct drilling.

Crop management systems

A main conclusion is that the effects of crops (rotation and incorporation) as studied in the three experiments, exceed the effects of tillage systems.

There is a positive effect of the incorporation of crops on the aggregate structural stability measured by the *wet sieving analysis*. In the tillage - rotation experiment, plots with sunflower and moha (incorporated as green material) in the rotation, show a wet sieving diameter 9% higher when compared to plots under continuous cereal cropping (dry residues of the previous crop are incorporated when the primary tillage is performed for the next). In reference plots planted with fescue the increase is 17%. In terms of wet sieving diameter, these crops incorporated as green manures showing better results in the long term are sunflower, moha, and some legumes such as crotalaria and jack bean. This is possibly due to an intermediate C/N ratio of these crops that helps to stabilize structure for longer periods. Alfalfa shows a positive effect as well, measured shortly after the incorporation of this crop.

The values of *bulk density* (and thus porosity) clearly show differences between the three sites. For sites 1 and 2 the values for the top layer are high (1.35 to 1.42 g cm^{-3}). The B horizon of site 2, which is of argillic nature, has extremely high values. Site 3, on the other hand (a clay loam profile), shows the best condition with values of around 1.15 g cm^{-3}. In all three experiments bulk density is influenced by the incorporation of green crops. Values 3 to 5% lower are found in the top soil when comparing crop incorporation with either continuous cropping or bare fallow. Below the depth of tillage (mechanized or by hand), the bulk density is higher. With respect to the crops studied as green manures, sunflower and crotalaria show beneficial effects in lowering the bulk density, crotolaria even in the B horizon.

In terms of *biomass respiratory activity* and *resistance to penetration* no clear differences between treatments were found, but in general there are signs that some crops cause an improvement in the physical status of the soil as shown by these indicators. These crops are sorghum, moha and legumes such as crotalaria and cowpea.

With respect to hydraulic properties, there is an effect of crop incorporation on the *saturated hydraulic conductivity*. Site 2, has a relatively high K_{sat} value in the A horizon (sandy texture). This value is doubled by the incorporation of sorghum or sunflower and it is increased as well by the incorporation of crotalaria, although in a lesser amount. In the B horizon, with an extremely low value, no short term changes can be reported due to the various crops. Sorghum, sunflower and crotalaria also cause significant increases in the rates of *infiltration* measured with a small rainfall simulator.

No short term effects (neither positive nor negative) of the green manuring were detected in the *yield of the winter cereal crop* .

Combined effects: Only for the bulk density a significant combined effect of rotations and tillage systems was found, showing a beneficial action of the root systems of sunflower and moha under reduced tillage and direct drilling.

Soil management, physical status and erodibility

Under field conditions

The indicators of physical status described before, when considered individually, do not allow precise conclusions about the implication of the changes measured. Thus, indicators were studied further on their relationships with measurements of soil loss by means of natural or simulated rainfall, and by measuring the susceptibility for crust formation.

As a direct effect, residues on top of the soil and those partially incorporated, reduce the *splash* caused by natural rainfall. However, no clear relationships between the amount of splash and indicators of stability of structure were found. In the tillage - rotation experiment, the relationship is slightly positive, shown by the fact that soils under crop rotations with sunflower and moha do have a higher wet sieving diameter, but still show the highest amounts of splash. This is explained by the fact that under low stability conditions a protective crust is formed, and under higher stability conditions, there is an easier detachment of stable aggregates. On the other hand, in the summer green manuring experiment, a negative relationship was found, where plots with the lowest wet sieving diameter showed the highest amounts of splash. This is explained by the fact that it is a sandy soil, where there is no formation of a crust to prevent detachment by rainfall. This explanation, for apparently contradictory results, was confirmed by literature as reported.

When *the amounts of soil loss* are measured by means of a small rainfall simulator, there is a significant influence of the amount of green residues incorporated in reducing the losses. The crops showing clear beneficial effects are sorghum, sunflower, alfalfa and serradela. Plots where these crops were partially incorporated, have a soil loss one fifth of that from bare fallow plots.

The relevance of crust formation was studied by determining a *sealing index*, in the winter green manuring experiment (site 3). A positive effect of the partial incorporation of alfalfa (plots with high wet sieving diameter) is evident. In spite of a number of practical problems, the results obtained and the background of the methodology led us to an elaboration of the study and development of this index.

Under laboratory conditions

In order to clarify the results found in our field experiments, the relationship between soil physical status and amount of soil losses and runoff was also studied in the laboratory, using a standardized methodology that allowed for more general conclusions. The results obtained in the field led us to the choice of a number of possibly useful indicators to be assessed in more detail in the laboratory. In that respect, soil samples were artificially prepared (precompacted at various moisture contents) to obtain a range of structural status, expressed by the wet sieving diameter measured after air drying and crumbling of the compacted samples. The limits for the moisture range are defined as the points where structure changes under compaction to 4 bar (under various moisture contents). The lower limit (L) corresponds to the moisture content where the value of the log of the air permeability (in m^2) is -12. The upper limit

(H) corresponds to the moisture content where the M-P-V diagram has its lowest value (maximum compaction).

Splash from precompacted samples under simulated rainfall consistently decreases when the wet sieving diameter decreases, while the amount of runoff increases. This means that stable aggregates are easily detached by raindrops. When stability decreases, the strength of the crust which is formed will increase, in turn causing lower splash but also leading to higher runoff.

In particular the soil in site 3 shows a high sealing index and thus a high risk of crust formation in spite of its better actual physical condition. This result confirms that the sealing index is a good indicator to express the soil physical quality.

Assessment of soil quality with respect to risk of erosion

We developed a *Soil Quality Index* allowing to predict the behaviour of a certain soil when exposed to erosive rainfall. A number of physical indicators were found suitable from our field and laboratory studies. Soil behaviour under varying physical conditions was calculated using a water balance simulation model (SWIM).

It was found that the presence of a B horizon with a K_{sat} lower than 12 mm day^{-1} is the most relevant characteristic influencing the rate of runoff. The other characteristics influencing the rate of runoff, placed in a decreasing order of relevance are: the depth of the A horizon, the sealing index, the surface storage and the total porosity (bulk density).

Based on our field, laboratory and simulation data, decision tables are constructed to assess soil quality with respect to risk of erosion for each site under study. The results obtained are in agreement with our general knowledge of the sites.

This index allows to be aware of the physical and hydrological conditions of a certain soil to resist the erosive action of rainfall. It does not aim at calculating amounts of effective soil losses from a certain area, but should allow the user to take appropriate management decisions.

Our index is only partly contributing to the assessment of the general Soil Quality, as this is a very wide concept including physical, chemical and biological indicators, aiming at the assessment of potential productivity of soils in a sustainable frame. Although our index deals with soil structure and is based on "physical" parameters, processes such as crust formation and aggregate stability are influenced by chemical and biological aspects as well.

The simulation of a deterioration of structural status, by subjecting soil samples at various moisture contents to a standard pressure, was found to be a useful tool in our investigations.

Agronomic implications

The partial incorporation of crops into the soil was found to have a positive effect on those physical properties that appear to highly influence the rates of runoff. In particular crotalaria, sunflower and sorghum consistently improve soil conditions.

In those cases where the initial physical status of the soil is poor, reducing the tillage intensity over a period of time of four years, did not show positive effects, whereas there are positive effects of including cover and green manure crops in the rotation.

Two effects of residue mixing can be distinguished. One is increasing the stability of soil structure and the other is the action as a physical barrier for raindrops. Both effects are desirable when the soil needs physical improvement to prevent erosion losses. Four years of permanent pasture without incorporation of vegetative material are not enough to produce an improvement in physical properties.

Both reduced or vertical tillage systems and the partial incorporation of crop materials into the soil showed positive effects on soil structure. When physical conditions are poor, our results indicate that a <u>combination</u> of improved crop management and tillage is required to improve the soil physical condition of the arable layer. Green manure incorporation together with vertical tillage during some years, can be thought as appropriate to bring the profile to such a condition from where reduced tillage or direct drilling could be successful.

The presence of an argillic B horizon appears to be a very important characteristic influencing the rates of runoff. Cover crops incorporated as green manures were not found to have a positive effect on the structure of this horizon, apart from crotalaria which showed a slight improvement. Other crops with the ability to develop deep penetrating root systems would be worth studying. A study in the use of such crops might include a comparison with tillage systems using deep chiselling or subsoiling.

Susceptibility for crust formation was also found to strongly influence the infiltration and thus the rate of runoff. In our study it was possible to reduce this susceptibility by keeping the soil surface covered thus reducing the impact of raindrops.

In Uruguay, attempts to prevent soil erosion have been based mainly on modifying landform and slopes. This led to the design and construction of grass strips and/or terraces. Effects of these, generally costly, measures are often disappointing.

Our study dealt with measures focusing on the soil itself and stresses the need of quantifying certain characteristics to serve as a guide for management. Some of these characteristics can easily be observed by farmers and advisors, such as the presence of a B horizon and the depth of the A horizon. Others require rather simple laboratory determinations that could be carried out by extension services.

SUMMARY

Of the many factors influencing soil quality control, in this research we deal with management possibilities, as these could be the most easily adopted by average farmers in Uruguay. According to this consideration we posed several questions to serve as guidelines for our research and work methodologies.

Introduction.
Chapter 1. Continuous cropping in agricultural areas in Uruguay have caused soil physical degradation and soil losses due to rainfall erosion. Although this has been reported in several local studies, the relationships between management, physical status and risk of erosion have not been quantified to allow for precise recommendations to farmers. This research aims at evaluating the changes in soil physical properties due to soil management and at determining to what degree the physical condition of the soil accounts for losses due to rainfall erosion.

Research context and hypotheses.
Chapter 2. The climate in Uruguay is temperate, with rainfall in all seasons and with a concentration of erosive storms in spring and summer months. Major soil types are Phaeozems of varying textures depending on the parent materials from which they are formed. In most of the cases an argillic B horizon occurs with unfavourable physical conditions. Topography in the areas devoted to agriculture is undulating with slopes of up to 15%. This is one of the reasons for erosion, together with excessive tillage, ineffective control measures and several socio-economic aspects. In this study, the following hypotheses are posed: a) Tillage practices are excessive. b) Physical improvement and a reduction of soil losses can be achieved by reduced tillage and by incorporation of crops biomass. c) The permeability of the argillic B horizon must be improved to obtain a better performance of the soils with respect to rainfall erosion.

Theoretical framework.
Chapter 3. It presents a review describing the actual knowledge of the effects of soil management (tillage, traffic, crop rotations and green manure incorporation) on soil physical status expressed by several indicators such as penetrometer resistance, bulk density and porosity, seedbed quality, stability of

structure and soil hydraulic properties, both of the A and B horizons. To study the effect of the physical status on soil losses due to rainfall erosion, the selected indicators are the amount of splash and of runoff. Modelling is introduced as a fast tool to predict rainfall redistribution under varying soil conditions and thus to provide limiting values for the definition of a soil structure quality index to assess risk of erosion.

Materials and methods.

Chapter 4. Three experiments are conducted:

i) A tillage - rotation experiment with 17 treatments consisting of 4 tillage systems (conventional, vertical and reduced tillage and direct drilling), 4 crop rotations (continuous winter cereal cropping and cereal cropping in rotation with red clover, sunflower or moha) and one reference plot sown with fescue at the beginning of the experiment. The crops in rotation with the winter cereal, are included both as cover crops and to incorporate them as green manures.

ii) A summer green manuring experiment where 8 summer crops are studied on their effects when they are incorporated into the soil, in comparison with a bare fallow plot.

iii) A winter green manuring experiment, where 5 winter crops are studied with the same purpose described under ii.

Several widely used field and laboratory analyses are carried out on samples taken from the three experiments in order to quantify the indicators of physical condition. This condition is then related to measurements of soil losses due to natural and simulated rainfall (splash, runoff and infiltration) performed both in the field and in the laboratory on natural aggregates. A higher standardized methodology is followed as well, to allow for a more precise laboratory study of the relationships between physical condition and soil losses. It consists of preparing a range of varying structure conditions by compacting premoistened aggregates (with various moisture contents) to a standard pressure. These compacted samples are subjected to a simulated rainfall. The stability of structure and the susceptibility for crust formation are by this way related to splash and runoff losses.

Results and discussion.

Chapter 5. Although no hard results are found from our field experiments on the influence of management on physical condition, there is a general indication of improvement in the top layer, due to reduced or vertical tillage and to green manuring. The crops showing larger effects are sunflower (*Helianthus annuus*), sorghum (*Sorghum bicolor*) and several legumes such as crotalaria (*Crotalaria juncea*), alfalfa (*Medicago sativa*) and serradela (*Ornithopus sativus*). Moreover crotalaria and sunflower cause improvements in the B horizon.

When a range of structure conditions is created in the laboratory and analyses are made on those samples, the results are clear to show that the poorer the structure (expressed by a lower wet sieving diameter and by a lower K_{sat}), the lower is the amount of splash and the higher the amount of runoff obtained under rainfall simulation. This results led us to accept the wet sieving diameter as a good indicator of physical status, although in the field the results are contradictory. Reasons for those contradictory results are the lack of precision about time for sampling and period of storage of the samples.

Also under laboratory prepared conditions, the sealing index (ratio between K_{sat} after and before rainfall simulation) gives a good indication of the susceptibility of the different soil types for crust formation.

Modelling of water behaviour on layered profiles.

Chapter 6. Several conditions are simulated for the three sites by using the SWIM model, as follows. i) The different structure conditions are simulated by means of varying the surface soil storage capacity and the values for bulk density of the A horizons. ii) The presence of a crusted top layer by varying the values of K_{sat}. iii) The presence or absence of a B horizon. iv) The occurrence of an eroded profile (by shortening the depth of the A horizon). The results allow to see the expected variations on infiltration for each case, thus on the amounts of runoff. The presence of the B horizon appears to be the most relevant feature conditioning water infiltration and movement in the soil. It is followed by the presence of a crusted layer and then, by the variations in structure conditions of the A horizons (as a result of different soil management systems).

Assessment of soil quality in relation to risk of erosion.

Chapter 7. Based on the results obtained in our study, we propose a method of assessment of soil quality for each site. The characteristics selected to be included in decision tables are placed according to their relevance to assess the ability to resist erosion. From higher to lower they are: i) presence of a B horizon, ii) depth of the A horizon, iii) susceptibility for crust formation expressed by the sealing index, iv) general structure conditions expressed by the wet sieving diameter and by the total porosity. As a result, the soil quality is assessed as high, medium or low, expressing respectively a low, medium and high risk of erosion. Our final recommendation is that soil management needs to be selected depending on the quality assessed to that specific site.

Agronomic implications and research needs.

Chapter 8. After going through several field experiments, laboratory analyses and modelling of water redistribution, we present a system to assess soil quality in order to express its ability to resist degradation and to avoid runoff, based on accurately measurable data. This allows to select the appropriate soil management system either to maintain or to improve that quality. When the quality is defined as low, it is necessary to consider a combination of tillage system (based mainly on chiselling) and crop incorporation (green manures). When it is defined as medium, it is possible to improve it by means of selecting an appropriate rotation system to allow the soil to be covered as long as possible and with crops being incorporated. It is possible to reduce tillage intensity to a minimum in this case. Of the crops evaluated in this research, crotalaria, sunflower and sorghum are those causing larger improvements in soil physical conditions.

Soil hydraulic properties (mainly of the B horizon) are relevant on their effects on the redistribution of rainfall in layered profiles. The need for future research points to the study of tillage systems (chiselling, subsoiling) in combination with a selection of crops with ability to develop extended deep penetrating root systems, in order to reduce the negative effects of the restricting layer.

SAMENVATTING

Er zijn vele factoren die de bodemkwaliteit kunnen beïnvloeden, zoals moedermateriaal, klimaat, vegetatie en gebruik. Dit onderzoek is gericht op de management aspecten, omdat deze, door de gemiddelde boer in Uruguay, het makkelijkst kunnen worden aangepast. Op grond van deze keuze zijn verschillende vragen opgesteld om te dienen als leidraad voor het onderzoek en de werkmethoden.

Inleiding.
Hoofdstuk 1. Langdurig en permanent gebruik van de landbouwgebieden in Uruguay heeft bodemfysische degradatie veroorzaakt, resulterend in bodemverliezen door regen erosie. Hoewel dit in diverse lokale studies is onderzocht, zijn de verbanden tussen management, fysische toestand van de bodem en erosiegevaar niet voldoende gekwantificeerd om precieze aanbevelingen te kunnen geven aan boeren. Dit onderzoek beoogt de veranderingen in bodemfysische eigenschappen als gevolg van bodemmanagement te evalueren en te bepalen in welke mate de fysische toestand van de bodem de schade als gevolg van water erosie verklaart.

Context en hypotheses.
Hoofdstuk 2. Het klimaat van Uruguay is gematigd met regen in alle seizoenen en met een concentratie van erosieve buien in het voorjaar en in de zomermaanden. De meest voorkomende bodemprofielen zijn Phaeozems van verschillende textuur afhankelijk van het moedermateriaal waaruit ze gevormd zijn. In de meeste gevallen is er een argillic B horizont met ongunstige fysische karakteristieken. De topografie van de gebieden onder landbouw is heuvelachtig met hellingen tot 15%. Dit is een van de oorzaken van erosie, naast overmatige grondbewerking, ineffectieve beheersmaatregelen en diverse sociaal economische aspecten.

In dit onderzoek zijn de volgende werkhypothesen gesteld: a) Grondbewerking is overmatig. b) Fysische verbetering van de bodem en vermindering van verliezen kan bereikt worden door verminderde grondbewerking en door het inwerken van gewassen c.q. gewasresten. c) Een verbeterde doorlatendheid van de argillic B horizont zal leiden tot een betere weerstand van de bodem tegen water erosie.

Theoretische achtergrond.

Hoofdstuk 3. Hierin wordt een overzicht gegeven van de actuele kennis van de effecten van bodem management (bewerking, berijding, gewasrotaties en groen bemesting) op de fysische toestand van de bodem, uitgedrukt in verschillende indicatoren zoals penetrometer weerstand, bulk dichtheid en porositeit, zaaibed kwaliteit, structuur stabiliteit en bodemfysische eigenschappen, zowel van de A als van de B horizonten. Om het effect van de fysische toestand op bodemverliezen als gevolg van watererosie te onderzoeken zijn als indicatoren hoeveelheid splash (spaterosie) en runoff gekozen. Modellering wordt toegepast als een hulpmiddel om op een snelle manier verdeling van de regen in het bodemprofiel te voorspellen onder verschillende bodem condities. Hierdoor worden grenswaarden verkregen voor de definitie van een bodem kwaliteitsindex met als doel dreigend erosiegevaar vast te stellen.

Materiaal en methoden.

Hoofdstuk 4. Er zijn drie experimenten uitgevoerd:

i) Een bewerking - rotatie experiment met 17 behandelingen bestaande uit 4 bewerkingssystemen (conventioneel, cultivator =nietkerend, gereduceerde grondbewerking en directe inzaai), vier gewasrotaties (continu wintertarwe; wintertarwe in rotatie met rode klaver, zonnebloem en millet) en een referentie plot ingezaaid met luceme vanaf het begin van het experiment. De gewassen in rotatie met wintertarwe zijn zowel bedekkings (mulch)gewassen als groen-bemesters.

ii) Een zomer groenbemestingsexperiment, waarin het effect van het inwerken in de bodem van 8 zomer gewassen in vergelijking met een braak liggend proefveld is onderzocht.

iii) Een winter groenbemestingsexperiment, waar 5 wintergewassen zijn onderzocht met het zelfde doel als onder ii.

Een aantal algemeen gebruikte veld- en laboratoriumanalyses is uitgevoerd in de drie experimenten om de indicatoren voor de bodemfysische toestand te kwantificeren. Deze kwantitatieve gegevens zijn vervolgens gerelateerd aan de metingen van bodemverlies onder natuurlijke en gesimuleerde regenval (splash, runoff en infiltratie) uitgevoerd zowel in het veld als in het laboratorium met natuurlijke aggregaten. Getracht is ook een gestandariseerde methode te ontwikkelen om duidelijker de relatie tussen fysische toestand en bodemverlies te kunnen vaststellen. Daartoe is een reeks van structuur condities gemaakt door bevochtigde aggregaten te verdichten (bij verschillende vochtgehaltes) onder een standaard druk. Deze monsters zijn daarna (voor een deel na opbreken tot aggregaten) kunstmatig beregend. Op deze manier kon de stabiliteit van de structuur en de gevoeligheid voor korstvorming gerelateerd worden aan verliezen van bodemmateriaal en water door splash en runoff.

Resultaten en discussie.
Hoofdstuk 5. Uit de veldexperimenten met betrekking tot de invloed van management op de bodemfysische toestand, is er een algemene indicatie de structuur in de top laag verbetert als gevolg van gereduceerde en niet-kerende grondbewerking en groenbemesting. De gewassen met een duidelijk effect zijn zonnebloem (*Helianthus annuus*), sorghum (*Sorghum bicolor*), en verschillende leguminozen zoals Crotalaria (*Crotalaria juncea*), Lucerne (*Medicago sativa*) en Serradella (*Ornithopus sativus*). Crotalaria en zonnebloem hebben een verbetering van de B horizont te zien gegeven.

De resultaten van de laboratoriumproeven tonen aan dat des te armer de structuur is (uitgedrukt in een kleinere 'wet sieving' diameter en een lagere K_{sat}) des te lager de hoeveelheid spat erosie en des te hoger de runoff wordt onder gesimuleerde regenval. Deze resultaten maken het aannemelijk dat de 'wet sieving' diameter een goede indicator is van de fysische toestand, hoewel in het veld de resultaten minder duidelijk zijn.
Onder laboratorium omstandigheden geeft ook de 'sealing index' (de ratio tussen K_{sat} voor en na regenval simulatie) een goede indicatie van de gevoeligheid van de verschillende bodemtypes voor korstvorming.

Modelleren van water beweging in gelaagde bodemprofielen.
Hoofdstuk 6. Voor de drie proeflokaties zijn er verschillende situaties gesimuleerd door gebruik van het SWIM model, nml. i) Verschillende structuur toestanden van de A horizont: capaciteit van de oppervlakteberging en bulkdichtheid. ii) De aanwezigheid van een korst aan het oppervlak. iii) De aan- of afwezigheid van een B horizont. iv) Een geërodeerd profiel (ondiepe A horizont). Voor diverse situaties is de infiltratie en runoff onder voor Uruguay typische regenbuien berekend. De aanwezigheid van de B horizont blijkt de meest relevante factor die de water infiltratie en beweging in de bodem beïnvloedt. Daarop volgt de aanwezigheid van een korst en dan de variatie in structuur condities van de A horizont (als gevolg van verschillende landgebruikssystemen).

Bodemkwaliteit in relatie tot erosie gevaar.

Hoofdstuk 7. Gebaseerd op de resultaten van deze studie wordt een methode voorgesteld voor de omschrijving en vaststelling van de bodemkwaliteit. De geselecteerde karakteristieken worden in beslissings'bomen' opgenomen, gerangschikt naar hun belang in het tegengaan van erosie. Dit zijn resp.: i) de aanwezigheid van een B horizont, ii) de diepte van de A horizont, iii) de gevoeligheid voor korstvorming uitgedrukt in de sealing index, iv) de structuur toestand ruwheid en bergingscapactiteit uitgedrukt in de 'wet sieving' diameter en in de totale porositeit. Als resultaat wordt de bodem kwaliteit aangegeven als hoog, middel of laag (erosiegevaar).

Landbouwkundige implicaties en onderzoeksbehoefte.

Hoofdstuk 8. Gebaseerd op de verschillende veld-, laboratorium- en modelexperimenten, wordt een systeem voorgesteld om een uitspraak te kunnen doen over de weerstand tegen bodemdegradatie en het voorkomen van runoff, aan de hand van simpele, doch nauwkeurig te meten data. Aldus kan een geschikt bodem management systeem gekozen worden. Wanneer de kwaliteit als 'laag' wordt omschreven is het nodig een combinatie van een niet-kerende bewerking en een groenbemester toe te passen. Bij een kwaliteit 'middel' kan deze verbeterd worden door een geschikt gewasrotatiesysteem te kiezen om de bodem zo lang mogelijk bedekt te houden en gewassen in te werken. In zo'n geval kan de bewerkingsintensiteit tot een minimum beperkt worden. De gewassen, die duidelijk verbeteringen in de bodemfysische toestand gaven, zijn crotalaria, zonnebloem en sorghum.

De karakteristieken van de B horizont zijn belangrijk in verband met de verdeling van (regen)water in een gelaagd profiel. In dit verband is er behoefte aan onderzoek gericht op bewerkingssystemen (bijv. niet kerend, diepwoelen) in combinatie met een keuze van diep wortelende gewassen, om de negatieve effecten van een storende laag te verminderen.

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Curriculum vitae

Ana Terzaghi was born on the 10th of September 1952 in Paysandú, Uruguay. She obtained the degree of Agricultural Engineer at the Faculty of Agronomy (University of the Eastern Republic of Uruguay) in 1976. In 1983 she obtained the degree of Master of Science in Soils and Water at the Wageningen Agricultural University (with distinction). Major: Land Evaluation. (Thesis: Determination of the upper critical moisture content for tillage of 14 uruguayan soils to quantify the land quality Workability, and its use in computer-assisted simulations to predict workable periods).

From 1979 until 1995 she worked as a member of the scientific staff of the Soils and Water Division of the Ministry of Agriculture and Fisheries in Uruguay. Since 1984 as the Head of a Regional branch of the Division in Paysandú. From 1990 to 1996 she worked to obtain her PhD degree with field and laboratory reasearch in Uruguay and laboratory research at the Soil Tillage Department of the Wageningen Agricultural University. This study was made possible with (financial) assistance from the WAU (fellowship) and from IFS (the International Foundation for Science, Sweden) which provided funds to install a laboratory in Paysandú.

APPENDIX I

Tillage - rotation experiment - Site 1

Ia) Pit analyses 29.1.1993. Experimental Station EEMAC Paysandú. Ruta 3 km 373. Brunosol Eutrico Tipico (Uruguayan soil classification)

Depth (cm)	*0 - 8*	*8 - 18*	*18 - 43*	*43 - 62*	*>62*
Horizon	A_p (A_{11})	A_{12}	B_{21}	B_{22}	B_3
pH (H_2O)	5.9	5.9	6.3	6.5	7.4
pH (KCl)	5.0	4.9	5.1	5.2	6.5
		gram per 100 gram soil			
Total sand	27.5	27.4	17.0	14.9	19.7
Total silt	45.9	44.9	29.6	32.5	36.9
Total clay	26.6	27.7	53.4	52.6	43.4
Texture	L/CL	CL/L	C	C	C/SC
Organic matter	3.78	3.26	1.79	1.66	0.59
Organic carbon	2.19	1.89	1.04	0.96	0.34
Total nitrogen	0.169	0.151	0.1	0.08	0.045
C/N factor	12.95	12.51	10.4	12.0	7.56
		meq per 100 gram soil			
Ca	11.88	12.2	22.2	21.97	32.33
Mg	1.62	1.50	3.38	3.72	3.08
K	1.15	0.84	1.21	1.91	1.37
Na	0.03	0.07	0.13	0.17	0.15
Total Bases:	14.68	14.61	26.92	27.77	36.93
Al	----	----	----	----	----
Exch. Acidity (pH 7)	4.45	4.65	5.15	3.58	----
CEC (pH 7)	18.93	18.50	32.15	30.85	31.17
% base saturation	76.5	74.9	84.0	93.8	100
Excess of Ca	----	----	----	----	5.76 *

* Ca outside the exchange complex

Exchangeable acidity = CEC - Total Bases - Aluminium (Al)

Ib) *Overview of the experimental field*

Block I

Treatment number				
17	40	0	80	120
16	80	120	40	0
3	0	40	120	80
8	80	120	40	0
13	40	0	120	80
11	40	120	0	80
15	40	0	80	120
6	40	80	120	0

N fertilization level (kgN/ha)

120	40	80	0	14
0	120	40	80	1
40	0	80	120	5
80	0	120	40	4
40	120	80	0	12
40	0	120	80	10
80	120	40	0	9
40	120	0	80	2
120	40	0	80	7

↑
N

Block II

3	8	11	5	7	15	2	6
120	0	40	80	40	40	120	120
0	80	0	0	0	0	80	0
40	40	120	40	120	120	0	40
80	120	80	120	80	80	40	80

0	80	40	80	0	0	40	80	120
120	40	80	120	120	120	120	40	40
80	120	0	40	80	40	80	120	0
40	0	120	0	40	80	0	0	80
14	9	16	17	10	4	12	1	13

Block III

5	9	17	4	12	14	2	11
40	120	120	40	0	40	0	0
80	80	0	120	120	120	40	80
0	0	40	0	80	0	80	120
120	40	80	80	40	80	120	40

120	80	40	40	0	0	120	40	80
40	120	80	80	120	120	0	0	40
0	0	0	120	80	40	40	80	0
80	40	120	0	40	80	80	120	120
7	6	3	10	8	1	15	13	16

APPENDIX II

Summer green manuring experiment - Site 2

IIa) Pit analyses, 29.1.1993. Paysandú. Ruta 3 km 388. Planosol Subéutrico Melánico (Uruguayan soil classification)

Depth (cm)	*0 - 30*	*30 - 37*	*37 - 57*	*57 - 75*	*>75*
Horizon	A_p	A_2	B_{21}	B_{22}	B_3
pH (H2O)	5.3	6.0	6.6	7.1	7.8
pH (KCl)	4.5	4.7	4.9	5.6	6.8
		gram per 100 gram soil			
Total sand	66.9	77.2	63.5	58.1	57.5
Total silt	19.0	14.0	14.5	10.9	10.1
Total clay	14.1	8.8	22.0	31.0	32.4
Texture	SL	SL/LS	SCL/SL	SCL	SCL
Organic matter	1.71	1.48	0.14	0.05	0.03
Organic carbon	0.99	0.86	0.08	0.03	0.02
Total nitrogen	0.106	----	----	----	----
C/N factor	9.37	----	----	----	----
		meq per 100 gram soil			
Ca	5.05	2.01	9.33	13.7	15.36
Mg	0.64	0.19	1.44	2.64	2.99
K	0.18	0.05	0.21	0.36	0.41
Na	0.12	0.13	0.77	1.37	1.57
Total Bases:	5.99	2.38	11.75	18.07	20.33
Al	----	----	----	----	----
Exch. Acidity (pH 7)	1.84	0.54	1.36	0.89	----
CEC (pH 7)	7.83	2.92	13.11	18.94	18.21
% base saturation	76.5	81.5	89.6	95.3	100
Excess of Ca	----	----	----	----	2.12 *

* Ca outside the exchange complex
Exchangeable acidity = CEC - Total Bases - Aluminium (Al)

IIb) Overview of the experimental field

N →

Block 1

		Moha			Bare fallow	Jack bean	
Crotalaria juncea			Guandú		Caupí maní		Sorghum
				Caupí moro			Sunflower

Block 2

	Sunflower	Caupí maní				Sorghum	Crotalaria juncea
	Caupí moro	Guandú			Jack bean		
Moha			Bare fallow				

Block 3

	Sorghum			Guandú		Crotalaria juncea	
Caupí moro					Bare fallow		
Sunflower		Jack bean		Caupí maní			Moha

APPENDIX III

Winter green manuring experiment - Site 3

IIIa) Description of the soil

Brunosol Eutrico Típico (uruguayan soil classification) with loamy sediments as parent material. An A horizon of 20 to 25 cm depth, clay loam to silty clay loam, with pH 6 to 6.5 and 5% organic matter. An argillic B horizon of 50-70 cm depth, clayey loam, pH 6.6 with 3% organic matter. In depth, a C_{ca} follows, with similar texture, and higher pH (8.2). Colours are dark brown varying to dark greyish brown, being lighter brown the C_{ca}, with concretions of $CaCO_3$

Partial analytical data:

	A horizon	B horizon
Clay %	30	40
Sand %	35	30
Silt %	35	30
Org. matter %	5.5	2.5
pH	6.0	6.5

IIIb. Overview of the experiment

↑ N

B I

	Ornithopus	Spergula	Avena			Medicago	
	Secale		Bare fallow				

B II

			Avena	Spergula			Secale
Bare fallow			Ornithopus				Medicago

B III

	Secale	Medicago	Bare fallow				
			Avena	Spergula			Ornithopus

APPENDIX IV

Statistical analyses for the three experiments

IVa) Tillage - rotation experiment. Analysis of variance for the dry sieving diameter (DSD).

Source of var	*df*	*MS*	*s*
Tillage systems (Til)	2	17.2	*
Rotation (Rot)	3	13.6	

Multiple range analysis

Til	*DSD*	*HG*
CT	13.9	a
VT	15.8	b
RT	16.1	b

Rot	*DSD*	*HG*
W-Rc	14.2	a
W-Mo	14.7	a
W	15.3	ab
W-S	17.0	b

Key to symbols. *df:* *degrees of freedom*
MS: *mean square*
s: *significancy (always at 5% level)*
HG: *homogeneous groups*

IVb) Tillage - rotation experiment. Analysis of variance for bulk density (BD) and total porosity (Por) for three layers (3-8 cm, 13-18 cm and 23-28 cm).

		MS and s				*MS and s*			
Source of variation	*df*	*BD 3-8*	*BD 13-18*	*BD 23-28*	*BD*	*Por 3-8*	*Por 13-18*	*Por 23-28*	*Por*
Tillage	3	0.004	0.007*	0.001		7.61	10.74*	0.31	
Rotation	3	0.006*	0.001	0.004		10.63*	0.97	4.39	
T x R	9	0.008*	0.001	0.001		10.70*	0.92	1.36	
Treat C	1	0.011*	0.001	0.000		22.37*	3.65	0.13	
Cov (MC)	1			0.014*				30.94*	
Depth	2				*				*

Key to symbols. *Cov (MC):* *moisture content taken as covariate*

Multiple range analysis for bulk density (BD) and total porosity (Por) for layer 3-8 cm (for identification of treatments (Tr) see table 6, page 42).

Tr	*BD*	*HG*	*Tr*	*Por*	*HG*
12	1.31	a	4	41.8	a
16	1.32	ab	8	42.3	ab
15	1.32	ab	17	43.4	abc
1	1.32	ab	3	45.3	bcd
6	1.33	ab	2	45.6	cde
5	1.33	ab	9	46.0	cde
14	1.34	ab	10	46.1	cde
7	1.35	abc	13	46.1	cde
9	1.36	abc	11	46.2	cde
10	1.36	abc	7	46.7	de
11	1.37	abc	6	47.0	de
2	1.38	abc	5	47.3	de
13	1.38	abc	14	47.4	de
3	1.38	bc	16	47.6	de
17	1.42	cd	1	47.6	de
8	1.46	d	15	47.9	de
4	1.47	d	12	48.4	e

Bulk density values depending on depth of sampling.

Depth	*BD*	*HG*
1 (3-8cm)	1.36	a
3 (23-28cm)	1.45	b
2 (13-18cm)	1.47	c

IVc) Summer green manuring experiment. Multiple range analysis for bulk density in three layers: 0-15 cm, 15-20 cm and B horizon (for identification of treatments (Tr) see table 7, page 45).

Tr	*0-15*	*HG*	*Tr*	*15-20*	*HG*	*Tr*	*B hor*	*HG*
4	1.22	a	*2*	1.46	a	*8*	1.63	a
7	1.25	ab	*4*	1.46	a	*7*	1.63	a
8	1.25	ab	*7*	1.49	ab	*1*	1.65	ab
6	1.26	ab	*5*	1.49	ab	*6*	1.66	ab
1	1.27	ab	*1*	1.50	ab	*9*	1.70	bc
3	1.27	ab	*9*	1.50	ab	*3*	1.70	bc
5	1.28	ab	*3*	1.51	ab	*5*	1.70	bc
9	1.29	ab	*6*	1.52	ab	*2*	1.74	cd
2	1.31	b	*8*	1.55	b	*4*	1.77	d

IVd) Winter green manuring experiment. Multiple range analysis for bulk density (for identification of treatments (Tr) see table 8, page 46).

Tr	*BD*	*HG*
4	1.09	a
3	1.10	a
2	1.10	a
6	1.11	a
5	1.12	a
1	1.16	a

IVe) Tillage - rotation experiment. Analysis of variance for structure determinations.

		MS and s			
Source of var	*df*	*WSD*	*Is_1*	*Is_2*	*Is*
Tillage	3	0.0287	0.338*	0.080	
Rotation	3	0.284*	0.053	0.066	
Treat C	1	0.438*	0.256	0.203*	
Depth					*

Key to symbols. *WSD: wet sieving diameter (mm)*
Is_1: Henin index of instability for layer 3-8 cm depth
Is_2: Henin index averaged for layers 3-8 and 13-18 cm depth

IVf) Summer green manuring experiment. Analysis of variance for structure determinations and for amounts of crop material incorporated.

Source of var	*df*	*MS and s* *WSD*	*GM*	*DM*
Treat	8	0.072	2.02×10^{9}*	8.6×10^{7}*

Source of var	*df*	BRA_1	BRA_2	*BRA*
Treat	8	63.95	11.75	
Depth	1			*

Key to symbols. *GM: amount of green material (kg ha^{-1})*
DM: amount of dry material (kg ha^{-1})
BRA_1: biological respiratory activity layer 0-15 cm (mg CO_2 per 100 g soil)
BRA_2: biological respiratory activity layer 20-40 cm

IVg) Winter green manuring experiment. Analysis of variance for structure determinations.

Source of var	*df*	*MS and s* *GM*	*WSD*
Treat	5	8.83×10^{7}*	0.302

IVh) Tillage - rotation experiment. Multiple range analysis for structure determinations.

Til	*WSD*	*HG*	*Rot*	*WSD*	*HG*	*Til*	Is_1	*HG*	*Rot*	Is_1	*HG*
VT	3.51	a	*W*	3.43	a	*DD*	0.80	a	*W-Rc*	0.95	a
RT	3.56	a	*W-Rc*	3.45	ab	*RT*	0.99	ab	*W-S*	1.01	a
DD	3.61	a	*W-S*	3.69	bc	*CT*	1.15	b	*W*	1.03	a
CT	3.61	a	*W-Mo*	3.71	c	*VT*	1.16	b	*W-Mo*	1.11	a
C	3.97	b	*C*	3.97	d						

Til	*Is_2*	*HG*	*Rot*	*Is_2*	*HG*	*Depth*	*Is*	*HG*
DD	0.91	a	*W*	0.96	a	*23-28 cm*	0.79	a
RT	0.96	ab	*W-Rc*	0.96	a	*13-18 cm*	0.97	b
CT	1.02	ab	*W-S*	0.96	a	*3-8 cm*	1.02	b
VT	1.10	b	*W-Mo*	1.11	a			

Key to symbols. *Til:* *tillage system*
Rot: *rotation system*

IVi) *Summer green manuring experiment. Multiple range analysis for structure determinations and amounts of crop materials incorporated.*

Treat	*GM*	*HG*	*Treat*	*WSD*	*HG*
2	0	a	*2*	0.54	a
6	22806	b	*8*	0.74	ab
3	25640	bc	*6*	0.75	ab
7	29640	bc	*3*	0.83	ab
9	31473	c	*5*	0.87	ab
5	32815	c	*4*	0.87	ab
1	64103	d	*9*	0.93	ab
4	64700	d	*1*	1.00	ab
8	83340	e	*7*	1.06	b

Treat	*BRA_1*	*HG*	*Treat*	*BRA_2*	*HG*	*Depth*	*BRA*	*HG*
2	22.9	a	*3*	12.6	a	*0-15*	31.2	a
8	26.9	a	*5*	12.8	a	*20-40*	14.7	b
1	27.5	a	*9*	13.2	a			
5	31.1	a	*6*	13.5	a			
6	31.7	a	*8*	14.6	a			
7	33.7	a	*2*	14.8	a			
4	35.2	a	*1*	15.9	a			
9	35.3	a	*7*	17.0	a			
3	36.7	a	*4*	18.2	a			

IVj) *Winter green manuring experiment. Multiple range analysis for structure determinations and amounts of crop materials incorporated.*

Treat	*GM*	*HG*	*Treat*	*WSD*	*HG*
1	0	a	*1*	0.99	a
3	4731	b	*4*	1.04	a
2	6181	b	*2*	1.08	a
4	7670	b	*5*	1.34	ab
5	13789	c	*6*	1.36	ab
6	14000	c	*3*	1.84	b

IVk) *Regression analyses*

Tillage - rotation experiment

		Independent variables				
					BD	*BD*
Dependent variables		*Is_2*	*DSD*	*WSD*	*3-8 cm*	*B hor*
WSD	a	0.13				
Spl_1	a	0.18	-0.07	0.12		
Spl_4	a			0.09		
Emerg/91	a		-0.32			
	b		*			
Yield/89	a				0.31	-0.15
	b				*	

Key to symbols.	*a:*	*correlation coefficient*
	*b *:*	*significancy at 5% level*
	Spl_1:	*splash (g) after first rain of 10.9 mm*
	Spl_4:	*splash (g) averaged for three rainfall events (10.9, 25.9 and 32.0 mm)*

Summer green manuring experiment

Dependent variables		Independent variables GM	BD (0-15 cm)	WSD	BRA_1	BD (15-20)
WSD	a	0.27			0.07	
K_{sat1}	a		-0.71			
	b		*			
Splash	a	-0.20		-0.31		
Yield	a		-0.35			-0.42
	b					*
Infilt	a	0.51				
	b	*				

Dependent variables		Independent variables WSD	BRA_1	GM	Infilt
Soil loss	a	-0.24	-0.26	-0.50	-0.86
	b			*	*

Key to symbols. *Infilt:* *amount of infiltration in mm*
Soil loss: *in g collected with the Kamphorst simulator*

Winter green manuring experiment

Dependent variables		Independent variables GM	WSD	GM_a	Infilt
WSD	a	0.08		0.38	
Soil loss	a	-0.49	-0.48		-0.55
	b	*	*		*
Infilt	a	0.40			

Key to symbols. GM_a: *excluding alfalfa*

IVl) Tillage - rotation experiment. Analysis of variance and multiple range analysis for resistance to penetration.

		Resistance to penetration. MS and s			
Source of var	*df*	*at 5 cm*	*at 10 cm*	*at 15 cm*	*at 20 cm*
Tillage	2				4361*
Treat C	1	*	*	*	*

Resistance to penetration at 20 cm

Til		*HG*	*Rot*		*HG*
VT	39.1	a	*W-Rc*	50.4	a
CT	51.7	a	*W*	70.6	a
RT	90.8	b			

IVm) Tillage - rotation experiment. Analysis of variance for the winter cereal crop emergence.

		MS and s
Source of var	*df*	*pl m^{-2} (avg 1989 and 1991)*
Tillage	3	2616
Rotation	3	721

IVn) Summer green manuring experiment. Analysis of variance for yield of barley.

		MS and s
Source of var	*df*	*Yield*
Treat	8	611831

IVo) Tillage - rotation experiment. Multiple range analyses for the winter cereal crop emergence.

Data averaged for 1989 and 1991

Til	*pl m^{-2}*	*HG*	*Rot*	*pl m^{-2}*	*HG*
DD	212	a	*W-Rc*	223	a
RT	228	ab	*W*	225	a
VT	233	ab	*W-S*	234	a
CT	248	b	*W-Mo*	239	a

Tr	*pl m^{-2}*	*HG*
8	180	a
7	207	ab
4	212	ab
12	218	ab
3	221	ab
6	222	ab
1	232	abc
2	235	abc
10	236	abc
13	237	abc
9	238	abc
16	238	abc
14	241	bc
15	242	bc
11	244	bc
5	284	c

IVp) Summer green manuring experiment. Multiple range analysis for yield of barley.

Tr	*Yield*	*HG*
6	2644	a
3	2711	a
4	2711	a
5	2989	a
8	3078	a
7	3278	a
1	3378	a
9	3778	a
2	3856	a

IVq) Tillage - rotation experiment. Analysis of variance for splash values, infiltration (double ring infiltrometer) and pF values.

Source of var	*df*	*MS and s* Spl_1	Spl_4
Tillage	2	2.884	1.386
Rotation	3	9.089 *	2.563 *

Source of var		*Inf after 80 min (mm min^{-1})*
Treatment	8	12.14

Source of var		pF_0	pF_1	pF_2	$pF_{2.7}$	$pF_{3.7}$	$pF_{6.1}$
Treatment	5	4.4	3.86	3.82	3.82	7.19	4.9

IVr) Summer green manuring experiment. Analysis of variance for: splash values (cups), for soil losses and amount of infiltration determined with the Kamphorst simulator, and for saturated hydraulic conductivity.

Source of var	*df*	*MS and s* *Splash*	*Soil loss*	*Infilt*	K_{sat1}	K_{sat2}	K_{sat3}
Treatment	8	0.622	15.5 *	7.32 *	89134	62750	13.6

Key to symbols. K_{sat1}: *saturated hydraulic conductivity layer 2-7 cm (mm day^{-1})*
K_{sat2}: " " " *layer 15-20 cm*
K_{sat3}: " " " *B horizon*

IVs) Winter green manuring experiment. Analysis of variance for soil losses and infiltration.

Source of var	*df*	*MS and s* *Soil loss*	*Infilt*
Treatment	5	25.68	5.54

IVt) *Tillage - rotation experiment. Multiple range analysis for splash, infiltration and pF values.*

Til	*Spl_1*	*HG*	*Rot*	*Spl_1*	*HG*	*Til*	*Spl_4*	*HG*	*Rot*	*Spl_4*	*HG*
RT	5.25	a	*W-Rc*	4.38	a	*RT*	3.06	a	*W-Rc*	2.67	a
VT	5.70	a	*W-S*	5.82	b	*VT*	3.45	ab	*W*	3.46	b
CT	6.23	a	*W*	5.88	b	*CT*	3.74	b	*W-S*	3.59	b
			W-Mo	6.82	b				*W-Mo*	3.94	b

Treat	*Infilt*	*HG*
11	0.216	a
17	0.542	ab
9	0.791	ab
7	3.192	abc
3	3.317	abc
6	3.958	abc
1	4.545	bc
5	5.054	c
2	5.458	c

Tr	*pF_0*	*pF_1*	*pF_2*	*Tr*	*$pF_{2.7}$*
7	48.97 a	47.95 a	44.69 a	*7*	41.4 a
9	49.54 a	48.16 a	44.82 a	*9*	41.7 a
1	50.32 a	49.17 a	46.40 a	*17*	42.7 a
5	51.30 a	50.13 a	46.57 a	*5*	43.1 a
17	51.51 a	50.18 a	46.59 a	*1*	43.2 a
3	52.07 a	50.67 a	47.58 a	*3*	44.5 a

Tr	*$pF_{3.7}$*	*Tr*	*$pF_{6.1}$*
7	31.7 a	*17*	8.79 a
17	32.4 a	*5*	9.54 a
1	32.6 a	*7*	9.67 a
5	33.4 a	*1*	10.05 a
3	34.8 a	*9*	10.87 ab
9	35.7 a	*3*	12.44 b

IVu) Summer green manuring experiment. Multiple range analyses for splash, soil losses and infiltration and for saturated hydraulic conductivity

Tr	*Spl*	*HG*	*Tr*	*Soil loss*	*HG*	*Tr*	*Infilt*	*HG*
6	2.00	a	4	1.33	a	2	10.2	a
7	2.10	ab	8	3.33	ab	6	11.6	ab
4	2.20	ab	6	4.51	abc	9	11.2	ab
5	2.23	ab	7	4.75	abc	3	12.1	ab
8	2.25	ab	5	5.39	bcd	1	12.1	ab
3	2.32	ab	1	5.70	bcd	7	13.1	b
9	2.36	ab	3	5.96	bcd	5	13.1	b
1	2.76	ab	9	7.82	cd	8	13.6	bc
2	3.49	b	2	9.03	d	4	15.7	c

Treat	K_{sat1}	*HG*	*Treat*	K_{sat2}	*HG*	*Tr*	K_{sat3}	*HG*
2	394	a	8	70	a	3	0.1	a
6	484	a	5	89	a	6	0.1	a
5	642	ab	3	117	a	7	0.3	a
3	670	ab	1	122	a	5	0.7	a
7	677	ab	4	151	a	9	1.0	a
1	686	ab	9	217	a	1	2.0	ab
9	799	ab	2	352	a	2	2.8	ab
8	832	ab	6	376	a	4	3.2	ab
4	960	b	7	467	a	8	8.2	b

IVv) Winter green manuring experiment. Multiple range analyses for soil losses and infiltration.

Tr	*Soil loss*	*HG*	*Tr*	*Infilt*	*HG*
6	1.34	a	1	14.2	a
3	1.94	ab	2	14.4	a
5	2.56	ab	5	15.4	ab
2	4.40	ab	4	15.8	ab
4	5.17	ab	3	16.7	ab
1	9.29	b	6	17.7	b

IVw) Winter green manuring experiment. Analysis of variance for Sealing Index.

Source of var	*df*	*MS and s* *SI*
Treatment	5	16.3

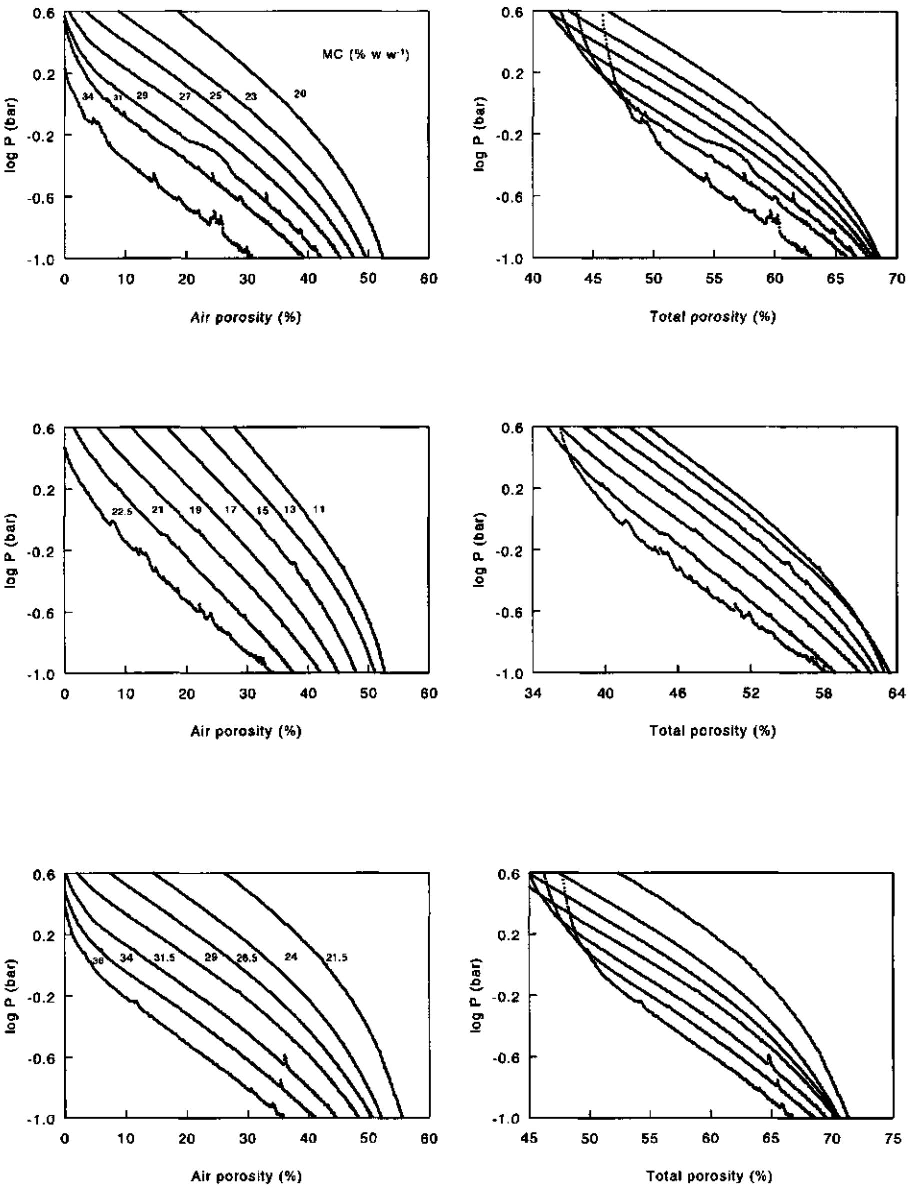
Multiple range analysis

Tr	*SI*	*HG*
3	2.07	a
4	2.53	a
2	3.10	ab
5	6.23	bc
6	6.90	c
1	7.07	c

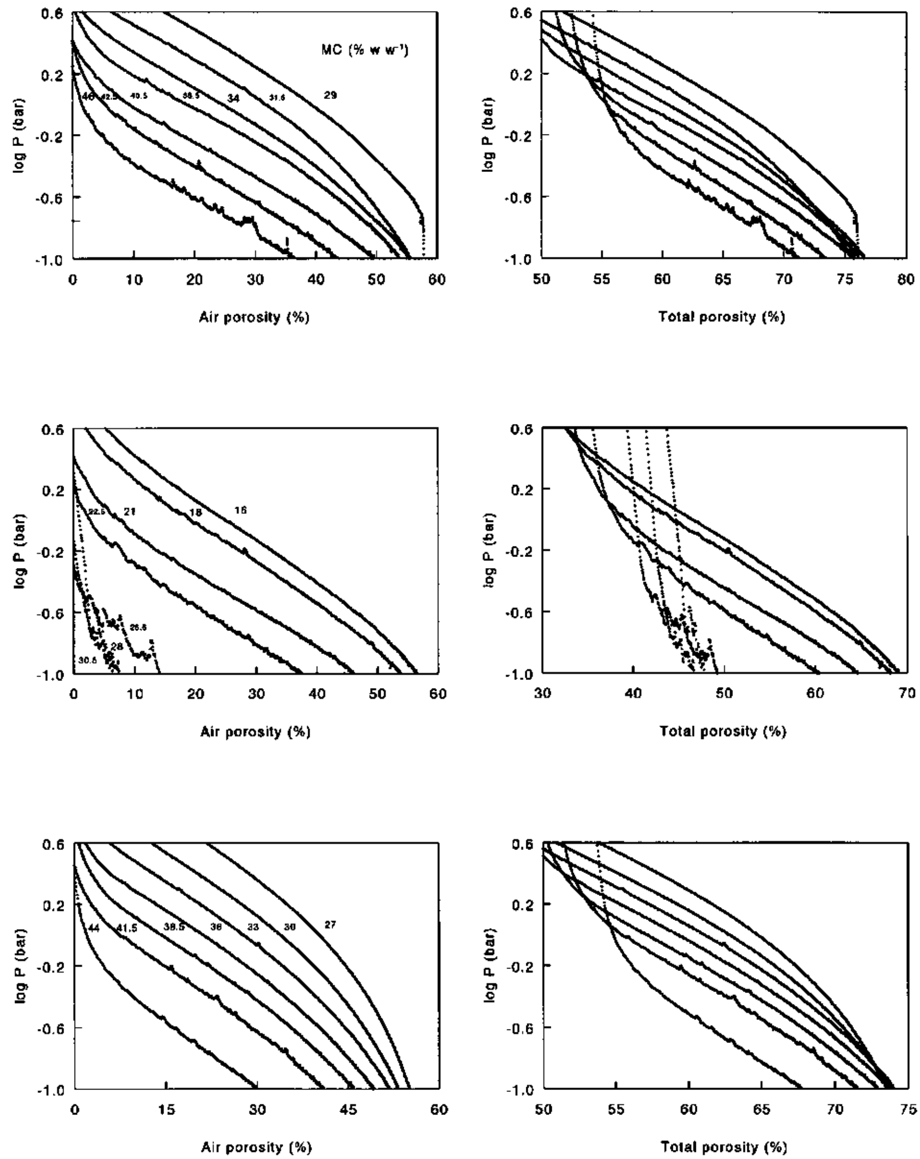
APPENDIX V

Results obtained for a laboratory prepared range of structure conditions

Va) Pressure - porosity curves for various moisture levels to a maximum of 4 bar, for A horizons (N.B. log 4 = 0.6).
Top: site 1. Middle: site 2. Bottom: site 3.



Vb) *Pressure - porosity curves for various moisture levels to a maximum of 4 bar, for B horizons (N.B. log 4 = 0.6).*
Top: site 1. Middle: site 2. Bottom: site 3.



Vc) Moisture content at pF 2 before and after compaction with increasing moisture contents

Site	*MC at pF 2 before*	*after*	*MC at compaction*	*Site*	*MC at pF 2 before*	*after*	*MC at compaction*
1 A	26.8	25.9	20	1 B	39.4	37.3	29
		26.5	23			37.8	31.5
		26.8	25			38.0	34
		27.4	27			37.7	36.5
		27.8	29			37.5	40.5
		28.3	31			37.6	42.5
		28.7	34			37.9	46
2 A	17.7	17.6	11	2 B	24.2	21.8	16
		17.8	13			21.5	18
		17.2	15			22.0	21
		17.6	17			21.3	22.5
		18.2	19			21.6	25.5
		18.6	21			22.2	28
		19.0	22.5			21.4	30.5
3 A	29.9	28.5	21.5	3 B	36.6	34.6	27
		28.7	24			34.8	30
		29.2	26.5			35.4	33
		29.8	29			35.1	36
		30.3	31.5			35.3	38.5
		30.6	34			35.6	41.5
		31.1	36			35.5	44

Vd) *Results obtained for the wet sieving diameter and with the rainfall simulation in the laboratory. For all 3 sites, A and B horizons (B on next page).*

Site	*MC (%w w^{-1}) at compaction*	*WSD (mm)*	*Total splash (g)*	*Splash (g m^{-2})*	*Runoff (%)*	*Infilt. (%)*	*Soil in runoff (g m^{-2})*
1 A	20	1.96	3.763	736	0	100	0
	22		2.833	554	9	91	34
	23	1.74					
	24		1.869	365	2	98	28
	25	1.29					
	26		1.368	267	7	93	42
	27	1.20					
	28		0.801	157	19	81	50
	29	0.94					
	30		0.670	131	14	86	30
	31	0.98					
	34	1.08					
2 A	11	1.90	7.167	1401	0	100	49
	13	1.48	6.671	1304	0	100	57
	15	1.39	6.110	1195	0	100	43
	17	0.99	4.047	791	0	100	35
	19	0.83	3.773	738	11	89	62
	21	0.81	3.517	688	14	86	68
	23	0.74	2.292	448	15	85	61
3 A	20		5.607	1096	0	100	61
	21	2.35					
	22		4.830	944	0	100	38
	24	2.23	3.847	752	3	97	30
	26	1.84	2.465	482	3	97	35
	28		2.032	397	4	96	35
	29	1.53					
	30		1.344	263	5	95	31
	31	1.21					
	32		0.972	190	6	94	33
	34	1.21					
	35		0.725	142	7	93	16
	36	1.20					

Site	MC (%w w[1]) at compaction	WSD (mm)	Total splash (g)	Splash (g m^{-2})	Runoff (%)	Infilt. (%)	Soil in runoff (g m^{-2})
1 B	28		4.575	894	0	100	44
	29	1.78					
	30		3.376	660	8	92	45
	32	2.06	3.743	732	11	89	55
	34	1.87	2.212	432	10	90	27
	37	1.49	0.619	121	9	91	17
	40	1.27	0.628	123	12	88	23
	43	1.50	0.562	110	17	83	34
	46	1.45	0.650	127	14	86	28
2 B	16	0.89					
	17		1.293	253			55
	18	0.68					
	19.5		0.272	53			8
	21	0.84					
	22	0.74	0.063	12			1
	24.5		0.087	17			2
	25	1.02					
	27		0.160	31			6
	28	0.86					
	29.5		0.396	77			25
	30	1.50					
3 B	26		3.189	623	0	100	30
	27	1.55					
	28		3.101	606	0	100	25
	30	1.29	3.778	739	1	99	26
	33	1.16	3.080	602	6	94	37
	36	1.27	2.373	464	9	91	26
	39	1.06	1.238	242	14	86	23
	41	1.01					
	42		0.677	623	15	85	9
	44	1.10					

APPENDIX VI

Inputs and results obtained with the SWIM model.

a) *Hydraulic properties for the layers considered in the three sites.*

Depth *cm*	ψ *cm*	θ *% v v*$^{-1}$	ψ_e *cm*	*b*	K_{sat} *mm day*$^{-1}$
Site 1					
0-15	-100	0.456	- 5	8	200
15-30	-100	0.391	- 8	12	150
30-60	-100	0.419	-10	20	2.4
Site 2					
0-15	-100	0.484	- 1	8	700
15-30	-100	0.400	- 1	8	220
30-60	-100	0.353	- 5	13	2.4
Site 3					
0-25	-100	0.539	- 4	7	400
25-60	-100	0.465	- 7	15	100

b) *Results obtained in order to make the decision tables to rate soil quality with respect to the ability to resist the impact of rainfall causing erosion*

Sequence of horizons	*Depth of A horizon*	*Sealing Index*	*% Runoff*	*% Inf*
Site 1				
A - B	15 cm	-	44	20
A - B	45 cm	-	35	29
A	60 cm	-	3	68
A	60 cm	10	13	62
Site 2				
A - B	15 cm	-	43	25
A - B	45 cm	-	34	35
A	60 cm	-	1	78
A	60 cm	10	10	76
Site 3				
A	60 cm	-	0	67
A	60 cm	15	10	63