TILLAGE FOR SOIL AND WATER CONSERVATION IN THE SEMI-ARID TROPICS

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TILLAGE FOR SOIL AND WATER CONSERVATION IN THE SEMI-ARID TROPICS

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Stellingen

1. A minimum of tillage is needed on hardsetting and crusting soils of the semi-arid tropics. No-tillage on such soils is only feasible in higher rainfall areas with more than 1000 mm rain per year.
   - this thesis

2. In view of the high draught requirements for tillage on hardsetting and crusting soils in West Africa, and the problems associated with the use of animal draught, motorization of tillage would be the best solution for agricultural intensification. Yet this development has a long way to go.
   - this thesis

3. Investments in tillage in semi-arid West Africa should always be accompanied by investments in fertilizer.
   - Mokwunye, A. U., A. de Jager, and E.M.A. Smaling (Eds.), 1996. Restoring and Maintaining the Productivity of West African Soils: Key to Sustainable Development, Miscellaneous Fertilizer Studies, IFDC Africa, No. 14., 94 p.

4. Models containing functional and mechanistic components are best suited for simulating the effects of tillage on sealing or crusting of soils and on crop production.
   - this thesis

5. In sealing, crusting and hardsetting soils, all agronomic measures (including tillage) to attain sustainable crop production should be aimed at an increase in soil organic matter.
   - this thesis
   - NN, 1997. Management of carbon in tropical soils under global change: science, practice and policy. Geoderma (special issue) 79 (1-4): 1-277.

6. The soils in Paraná, Brazil are examples of soils on which no-tillage is technically the best farming option.
   - this thesis
   - Derpsch, R., C.H. Roth, N. Sidiras and U. Köpke, 1988. Erosionsbekämpfung in Paraná, Brasilien: Mulchsysteme, Direktsaat und konservierende Bodenbearbeitung. Schriftenreihe der GTZ nr. 205, 266 p.

Voor Annelies

ABSTRACT

Hoogmoed, W.B., 1999. Tillage for soil and water conservation in the semi-arid tropics. Doctoral Thesis. Wageningen University, the Netherlands, (xii + 184 pp.) With ref. - With summary in Dutch, ISBN 90-5808-026-9

Soil tillage plays an important role in crop production in the semi-arid tropics (SAT). A large percentage of the soils found in these regions is light, contains non-swelling or shrinking clay minerals and has a low soil organic matter content. As a result, soils have a low structural stability and can be characterized as 'sealing, crusting and hardsetting'. The formation of seals, crusts and hardset layers is aggravated by the aggressive and unpredictable nature of the rainfall, which is also typical for the SAT. Important problems are the large losses of rainwater due to runoff from the sealed and crusted surfaces, the poor emergence from crusted seedbeds, and the very high energy requirements for tilling (breaking up) the hardset and crusted soils.
In this thesis, research is reported from West Africa and Brazil. A quantification of the rainfall characteristics supports the calculation and design of tillage systems causing an optimum surface configuration in terms of water infiltration and emergence. In the West African Sahel area most fields are gently sloping (1-3%) and runoff is a widespread phenomenon; on the average 25% of the rain (mainly in the form of a few large storms during the rainy season) is lost by runoff. It was found that fine sandy soils from Mali, are very sensitive to crust formation. Sealed soils showed a very low infiltration capacity. On untilled soils the presence of a crust is a permanent feature. Tillage destroys the crust and increases the surface storage for rainwater. The crust-breaking effect will last for only a few rainshowers, but the increase of surface storage is more permanent. A coarser sandy soil from Niger had less sealing problems, but showed a mechanical behaviour which is extremely dependent on the moisture content at the time of soil handling. Dry spells frequently cause wind erosion damage to seedlings. The traditional planting method (in hills) was found to be the best approach to reduce wind erosion damage. In view of the poor water holding capacity of these soils, the number of days available for planting millet is extremely small. Tillage (ploughing or ridging) resulted in better crop stands but may reduce the number of plantable days. Ridging without other tillage would, in view of timeliness and energy savings (animal traction), be the best approach.
In situations where energy is not limiting and heavy machinery is applied, risks of compaction and loss of favourable soil structure are high. No-tillage cannot always be applied because of economical reasons, loosening of compacted layers under conventional tillage remains necessary. The possibilities for the use of chisel ploughs on wheat stubble in a wheat-soybean rotation on sloping, erosion-susceptible red soils in the Brazilian State of Paraná were investigated.
Compared to conventional tillage systems with disc implements, chisel ploughing left more plant residue at the surface, a prerequisite for successful soil and water conservation. Fuel consumption for chisel ploughing was significantly lower than disc ploughing. Weeds and large amounts of straw, however, may cause considerable practical difficulties and require adequately dimensioned chisel ploughs and suitable sowing equipment.
Although hardly any specific simulation models for tillage are available, models in the discipline of tillage for soil and water conservation offer a useful support in research.

By combining simulation models for plant production and soil water movement (developed and adapted for application in the SAT), various scenarios of tillage for soil and water conservation were evaluated. It was found that water conserving tillage on poor soils as such has a very small yield-conserving effect because of the limitations set by the nutrient status. Elimination by tillage of the competition by weeds had a larger effect on the grain yield of a millet crop.
Seal/crust formation as measured by rainfall simulator experiments proved to provide a good input variable for modelling effects on infiltration.

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The cases have appeared as:

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Case 2: Hoogmoed, W.B. and Klaij, M.C., 1990. Soil management for crop production in the West African Sahel. I. Soil and climate parameters. Soil Tillage Res., 16: 85-103.

Case 3: Hoogmoed, W.B. and Derpsch, R., 1985. Chisel ploughing as an alternative tillage system in Paraná, Brazil. Soil Tillage Res., 6: 53-67.

Case 4: Klaij, M.C. and Hoogmoed, W.B., 1993. Soil management for crop production in the West African Sahel. II. Emergence, establishment, and yield of pearl millet. Soil Tillage Res., 25: 301-315.

Case 5: Hoogmoed, W.B., Berkhout, J.A.A. and Stroosnijder, L., 1992. Soil tillage options for water management under erratic-rainfall conditions. Homme, terre et eaux, Revue Marocaine des sciences Agronomiques et Vétérinaires, 22: 40-55.

Case 6: Stroosnijder, L. and Hoogmoed, W.B., 1984. Crust formation on sandy soils in the Sahel. II. Tillage and its effect on the water balance. Soil Tillage Res., 4: 321-337.

PREFACE

This thesis is about tillage and its role in soil and water conservation. The need to till the soil in order to produce food is commonly accepted and very often information about agriculture is illustrated by a picture of a farmer ploughing his land. Yet, because of the fact that tillage is performed since the beginning of arable farming, it has often been considered much more an art rather than a science. Tilling or cultivating the soil is hard work: often considered too much of a burden for all the men and women who have to break and turn the hard or sticky soil. Efforts for alleviating the job were made first of all by using animal traction, and early evidence of this was found in rock carvings in Sweden, on clay tablets of Sumerian times and e.g. on pictures in ancient Egyptian tombs. In all situations, the *ard*, the predecessor or 'prototype' of the mouldboard plough, pulled by animals was depicted. Much later, with the development of steam and fossil-fuel engines, tractors took over the job in the developing regions of Europe and the USA.

The dangers of indiscriminate application of tractors to open up new land were not recognised until the famous or notorious 'dust bowl' in the Mid-west of the USA in the late 30ies opened the eyes of many farmers and scientists. The "Plowman's folly" (Faulkner, 1943) can be considered as a landmark in the attitude towards mechanised production methods and resource conservation. Although there is an increasing awareness of the risks involved, this does not mean that everywhere agricultural production at acceptable levels can be achieved without manipulation of the soil. The needs for tillage remain in many situations, particularly in the tropical areas, where soils are poor in structure and fertility, where the climate is aggressive, and where unfortunately the means for the farmer to answer these needs are limited.

Some of abovementioned aspects of tillage in the semi-arid tropics are addressed to in this thesis. It is the result of my research activities carried out within the framework of the Tillage Laboratory, in various cooperative projects. First of all in a project with both the Faculty of Agriculture of the Hebrew University in Rehovot, Israel and the PPS project (Production Primaire au Sahel, Wageningen Agricultural University). Various aspects of tillage and its role in the water balance were studied in field experiments in Mali and Israel. Secondly, research was done at ICRISAT's Sahelian Center in Niger, where emphasis was given to agronomic aspects. Research on some other aspects of tillage was done in a project GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit) in Brazil, where attention was given to implements to be used in soil and water conservation.

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Furthermore I would like to thank Prof. Emer. Henk Kuipers who inspired me to take up the discipline of soil tillage during my studies and who invited me to join the Tillage Laboratory and to start investigating the problems of tillage in the tropics under his enthusiastic guidance.
A word of thanks also goes to Albert Boers, who carried out many jobs both in the laboratory and on the computer, the results of which are found in this thesis. He and Corrie Seves were always there in Wageningen to react to letters, faxes and e-mails from abroad requesting help.
A large number of students from Wageningen, as well as from Israel, Niger, Mali and Brazil participated in the research activities leading to this thesis. Their involvement is highly appreciated.

1. INTRODUCTION

Soil tillage, defined as 'the manipulation, generally mechanical, of soil properties to modify soil conditions for crop production' (SSSA, 1987) has, through the ages, been applied in farming systems where natural vegetation is replaced by arable crops. Obviously, the basic action in growing a plant is to place seeds in the soil, so always some minimal form of soil disturbance is required and presumably agriculture began as a system where a pointed stick was used to place seed in the soil. However, farmers[1] found that manipulation of the soil other than making a planthole could improve the growth and development of their crop. The positive effect of a good soil 'tilth'[2], as a result of tillage, was recognized.

1.1. The main functions of soil tillage

Today, research has given us a much better insight in, and an explanation of the effects of soil tillage, although definitively not all processes are well understood. We do know that tillage, as an activity modifying the structure of the top layer of the soil, has many direct and indirect effects and generally, we may distinguish a number of reasons why tillage could be done:

- To facilitate the production of a crop (preparing the arable layer to form an environment allowing an optimum germination, emergence and development of a plant),
- To control weeds (elimination of competition),
- To shape the topsoil in order to allow irrigation or an easier harvest of the underground parts of the crop
- To bury or incorporate organic material, fertilizer, pesticides etc.

The above reasons are rather obvious and straightforward. They guide the day-to-day decisions a farmer has to make during a cropping season. Crop production, however, is a process utilizing an important natural resource, the soil. Thus, in order to ascertain that the production system is sustainable[3], the quality and potential of this resource should not decrease.

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[1] In this text the farmer is referred to as 'he', but it is recognized that a large percentage of farmers world-wide (and particularly in tropical developing countries) are women.

[2] Tilth can be described as the physical condition of soil as related to its ease of tillage, fitness as a seedbed and its impedance for seedling emergence and root penetration (SSSA, 1987).

[3] The description of sustainable agriculture by the Technical Advisory Committee of the Consultative Group of International Agricultural Research: 'Management of resources for agriculture to satisfy changing human needs, while maintaining or enhancing the quality of the environment and conserving the natural resources' (TAC/CGIAR, 1988).

This leads to some additional objectives that always should act as guiding principles in choosing tillage systems:

- Maintaining soil fertility (both chemical as well as physical)
- Protecting the soil against external factors leading to degradation

These objectives are particularly important in tropical situations, where climatic conditions such as high temperatures, extended dry periods and intensive wet periods with aggressive rainfall constitute increased risk factors.

Tillage operations are part of a crop production system and therefore this production system is the main determining factor. In making the choice for a certain tillage operation or system[4], the farmer may be well aware of the most important objectives, but he is usually facing many practical limitations and restrictions to what he actually can do.

1.2. Tillage issues

In this thesis, a number of issues concerning soil tillage and its relation to soil and water conservation (SWC) are treated. The most important ones are:

- *short term and long term effects:* not all manipulations of the soil which are positive in their immediate effect will also be positive over the years, slowly progressing structural deterioration may have to be corrected after longer intervals,
- *agronomic versus SWC requirements:* the ideal soil tilth for optimum crop growth usually is sensitive to aggressive weather forces, whereas a well-protected soil surface forms a poor environment for crop development,
- *costs and benefits:* the costs of tillage (expressed as money, time or energy and labour) are relatively high in low external input situations, and benefits (which may be expressed in terms of money, food, conservation of resources) are difficult to measure due to the complexity of the farming system,
- *the diversity in tillage systems:* a large number of factors have an influence on how tillage is done, guiding principles or requirements are balanced with restrictions due to limiting equipment, time, knowledge etc.

Abovementioned points will briefly be discussed here, they form part of the topics dealt with later in this thesis.

[4] Tillage *action*: the specific form or forms of soil manipulation performed by the application of mechanical forces to the soil with a tillage tool, such as cutting, shattering, inversion or mixing. Tillage *operation*: Act of applying one or more tillage actions in a distinct mechanical application of force to all or part of the soil mass. Tillage *system*: The chain or sequence of tillage operations performed over a cropping cycle.

1.2.1. Short term vs long-term effects

The majority of individual tillage operations is carried out because of a direct need, which usually is to modify (improve) the growing conditions of the crop. The effects of this intervention are typically short-term (visible in hours or days, e.g. seedbed preparation, weeding, ridging). Other operations, such as ploughing, may be applied with a purpose which is further away in time (weeks, months). Sometimes the effect is supposed to last for a longer period (e.g. subsoiling for breaking up disturbing layers, or tillage during fallow periods for water conservation). These effects may last for periods of more than one or two years.

On the other hand, long term effects may become visible when we consider a tillage system comprising of sequences or combinations of tillage operations. Examples of desired long-term effects are the shaping of the field surface (e.g. *'broad beds' for superficial drainage, terracing), improvement of soil structure* through increase of organic matter content etc. Undesired long-term effects are the formation of plough pans, subsoil compaction, exhaustion of soil organic matter (SOM) in the soil leading to deterioration of the structure of the soil, increase of draught requirements for tillage, reduction of the workable period etc.

1.2.2. Agronomic vs SWC requirements

Manipulation of the toplayer of the soil by tillage has a strong effect on the structure. Tillage directly changes bulk density, strength and homogeneity of the soil. These changes influence a.o. hydraulic characteristics and stability characteristics (important for soil and water conservation), but also the behaviour of the soil with respect to water, air, temperature and mechanical resistance, factors important for the growth of the plant, as is shown schematically in Figure 1.

The farmer is often faced with a conflict between agronomic and SWC-requirements. On the one hand, an optimum environment should be created for the germination, establishment and growth of crops. Although requirements differ per crop, in practice this means a fine, smooth, uniform and weed-free toplayer or seedbed, particularly for small-grained crops. On the other hand, soil and water conservation is generally best achieved by the creation of a stable soil surface, resistant to the destructive and erosive forces of water and wind. Though depending on soil type and climatic conditions, the best effects in arable cropping are achieved with a coarse, uneven soil surface, made up from large, stable clods, preferably supported by the presence of crop residues such as standing stubble or partly incorporated straw, or live vegetation.

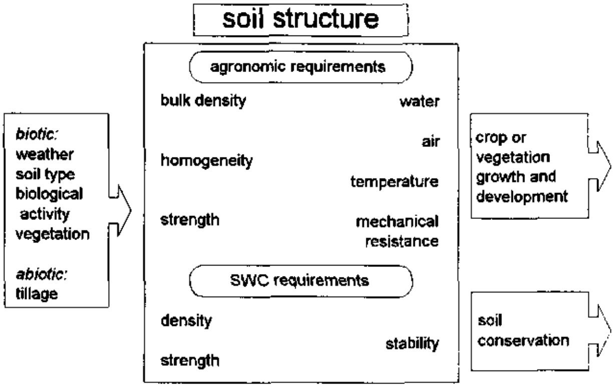

Fig. 1. *Tillage and its influence on soil structure.*

1.2.3. Costs and benefits

General remarks

Obtaining a high yield is a very important objective in agriculture but it should not be reached at all costs. In fact a farmer will try to obtain the highest possible profit; in general the difference between the money he gets for his crop, and the money he has spent in producing that crop. It is not essential to use the term money; if the crop is not sold but used by the farmer and his family, he will nevertheless justify the efforts to be made in producing the crop by evaluating the appreciation of the expected yield.

Tillage costs are only a part of all the costs of field operations, and apart from these, there are general production costs. The return side of the balance depends on the short-term only on the yield obtained, but on the longer term also on the quality of the resource base. In a high input farming system run on an economic base, costs of tillage often are a much smaller quantity than the value of the yield and thus a small yield increase would be sufficient to compensate the higher tillage costs. This often applies in temperate climates where erosion risk is negligible. On the other hand, when (in situations with an elevated risk for erosion) crop production can be accomplished with an alternative tillage system such as conservation tillage or no-tillage causing no or acceptable yield reductions, there will be an economic gain. An example is the success of the application of no-tillage in the southern states of Brazil (Derpsch et al., 1988).

In a low input farming system, the economic principles are often completely overruled by the practical constraints, where e.g. changes in a tillage system may imply the shift from manual labour to animal traction, and the required capital investment for draught animals and a plough maybe in the order of a year's income.

Soil and water conservation

Where it is very difficult in a non-market situation to talk about costs and benefits with respect to crops, it is even more difficult to talk about the economics of soil and water conservation. Effects of SWC are very difficult to measure and quantify, since the effects on crop yields are caused by improved water availability and possibly absence or reduction of seed and nutrient losses when runoff and erosion are decreased. Also, they may become visible after a number of years only, and benefits are not exclusively on the field or farm level, but also on e.g. the downstream area of the watershed where the measures took place.
At the costs side, a number of measures (such as terracing, stone or earth bunds etc.) is too large and too expensive to be taken on by just the farmer alone, so it is a matter of local community or government. As the effects of these measures are to last over many years, it is not easy to calculate costs on annual basis. An adapted type of tillage (system) in that respect is easier to express in terms of money. De Graaff (1997) has treated this subject in detail with examples from semi-arid regions in developing countries.

Energy

Crop production is one of the few processes whereby solar energy is collected and conserved in the form of organic material for use as food, fuel or building material. In the semi-arid and subhumid tropics more than adequate quantities of solar energy are usually available, although actual crop yields are lower than the yields which could maximally be obtained under such levels of solar radiation (due to deficiencies in water, nutrients, suboptimal temperatures, weed competition, pests, poor management etc.).
The agricultural energy balance is a complex subject and lies outside the scope of this thesis, but some data are presented here to indicate the position of soil tillage within the energy balance.
In many industrialized countries, energy for agricultural production usually accounts for less than 5% of the total (national) energy consumption. This is mainly 'commercial' energy (fossil fuels). In developing countries, where agriculture generally forms an important part of the economic activities, the utilization of commercial energy may be as low as 10% of the total consumption, the remainder coming from fuelwood or crop residue. Human and animal labour form an important part of the energy input for agricultural production.
The input part of the energy balances for agricultural systems applied in developed countries consists mainly of fuel, fertilizer, irrigation, machinery, transport, drying and on-farm processing. In these systems using conventional

tillage methods, tillage accounts for approximately 5% for irrigated and up to 15% for dryland systems (all factors are expressed in energy units). Fertilizers, mechanization and irrigation are the greatest energy consumers.
On the other hand, the energy input of subsistence farming or small-holders in developing countries is mainly associated with human and animal labour and only a very small proportion is expended on fertilizers, machinery, fuel and chemicals.

The absolute output (in terms of energy of the agricultural product) from the high-input system is much greater per unit area, but the output:input ratio is generally much lower than for low-input systems.
Pimentel and Heichel (1991) gave the following examples based on maize production in Mexico and the USA: for slash-and-burn (shifting cultivation) maize production with human labour only: output/input ratio 12.9, same conditions using draught animals: o/i ratio 6.3, highly mechanized (conventional) maize production: o/i ratio 3.3. In the human-labour system, labour accounts for 92% of the total input of 2.7 GJ ha^{-1}. In the animal draught system, human labour is 12% and animal draught 83% of the total input of 3.2 GJ ha^{-1}. In the mechanized system, labour input is in the order of 0.1%, machinery plus fuel is 25%, fertilizers and seed 43% and pesticides 7%, of a total input of 29 GJ ha^{-1}. Above figures do not take into account the solar energy[5]. It was observed that the human-labour system would be sustainable[6] for one person with 10 ha (fallow is needed), for the animal draught system 4 ha (using N-fixing green manure). The mechanized system is not sustainable, but results in a yield which is at least 3 times higher than the one produced under the other systems.

1.2.4. The diversity in strategies, systems, and tools

Worldwide, there is an enormous diversity in the way tillage is performed. In addition to the very wide range of soils, climate, and crops, leading to specific requirements, tillage as a core activity for the farmer has traditionally had a non-universal, site-specific application. Tools were made locally by farmer or blacksmith, techniques were applied as they were typical for a village or region. Even presently, many manufacturers of tillage equipment in the modern western society, only cater for regional demands.

Desired situations, such as optimum crop growing conditions, but also the best soil and water conservation can in principle be translated into ideal soil surface

[5] The energy input from the sun is many orders of magnitude larger than the input from farming activities: assuming 0.1% of photosynthetically active solar energy to be captured by growing plants, this leads to 60 GJ ha^{-1} annually.

[6] A sustainable system for producing food and fuels: persistent and renewable without detrimental environmental effects (according to Pimentel and Heichel, 1991).

conditions to be described as 'a fine and smooth seedbed' or 'a rough and cloddy surface with partial incorporation of crop residue'. (Sequences of) tillage operations can offer the technical solution in reaching these situations.

On the highest level of decision making, strategies may be developed addressing global, national or regional problems or problem-based objectives. Table 1 shows a number of these objectives and the general strategies of soil management which can be followed:

Table 1. *Objectives and derived strategies for soil management (source: Pierce and Lal, 1991).*

·	*objective*	*strategy*
a	reducing risks of global warming	- conservation of organic C in the soil, thus reducing CO_2 production - preserving or enhancing soil quality
b	reducing risks of water pollution	- farming by soil (precision farming) - soil erosion control
c	preventing soil degradation	- conservation tillage - appropriate land use - soil-enhancing cropping systems
d	maximizing profit	- sustainable agriculture - farming by soil (precision farming)

Many variations and modifications of these strategies can be produced, but the ones listed in the table are specifically important for the semi-arid tropics. Clearly, the strategies under objectives a and b are quite far away from the daily worries of the small farmer in the developing countries, but c and d constitute recognizable objectives.

Strategies have to be given a concrete form by following a crop production system which adheres to the principles set forward in those strategies. The translation of strategies into tillage operations or systems follows a number of levels, each one determined by certain boundary conditions. These levels are shown in Table 2. Only decisions on the lowest level (3) are within reach of most of the farmers, level 2 decisions require major investments, while the choices on level 1 can only be made with interference or support from e.g. (local) governments, thereby implying (longer term) changes.

Table 2. *Tillage: levels of decisions (adapted from Kuipers, 1985).*

	determinant	*description*
1	**resource** quality	The choice of a tillage system under a farming strategy as allowed by the nature of the resource base and the technical and socio-economical conditions.
2	**crop** production, **SWC** requirement	The choice of a certain chain of tillage operations to reach specific goals within a crop production system.
3	**tools** and **power** availability; **soil** behaviour	The choice and use of implements and power sources (e.g. plough, cultivator; tractor, animals, human labour).

1.3. Semi-arid tropics (SAT)

Approximately one-fourth of the world's population lives in arid and semi-arid areas; 1.6 billion people live in developing countries and regions affected by insufficient rainfall. Half of the workforce in these countries earns its living in and from agriculture (CGIAR, 1997). Rural people here are among the poorest in the world. The Green Revolution, successful because of the grain yield increases in situations with irrigated agriculture, or there where rainfall was not limiting, did not bring improvement for the farmers in the (semi-)arid dryland regions.

Desertification[7] is mentioned as a very serious degradation threat to drylands (Hurni et al., 1996). This is mainly caused by three factors: overgrazing, excessive use of wood (fuel) and inappropriate agricultural practices. The last factor is most prominent in dryland cropping areas, especially through inappropriate management of rainwater and loss of soil fertility. Estimations are that around 4400 million ha of rangeland are desertified, and 400 to 500 million ha rainfed cropland, of which one-third severely (Pimentel, 1993).

Extension of the irrigated area is not a feasible solution, so answers for improvement must be sought in developing more productive and sustainable farming practices. This is not an easy task in view of the very poor physical and chemical characteristics of the majority of the soils found in these areas, and the aggressiveness and harshness of the climate. Further in this thesis, some aspects of the approaches towards improving these farming practices, (particularly the tillage) will be treated.

[7] Desertification as defined at the UN conference on Environment and Development in 1992: 'degradation of land resources in arid, semi-arid and dry sub-humid areas, caused by different factors including climatic variations and human activities'

1.4. Soil and water conservation

The term 'Soil and water conservation' comprises two components who are very closely related, but who are not necessarily always linked. In case of rainfall erosion, an important aspect of soil conservation is indeed the conservation of water. With respect to protection of soil against wind erosion, water conservation plays an insignificant role. On the other hand, in the semi-arid tropics, water conservation as such is a very important objective in dryland or rainfed agriculture, also under conditions where there is no risk for soil erosion.

Soil conservation as a science was hardly known before the beginning of the 20th century. Yet natural erosion by wind and water is tens of thousands of years old, and the ground of many regions is simply the result of deposition of soil material eroded elsewhere. The recognition of the importance of erosion induced or accelerated by man came only recently. Hudson (1985) quotes references to erosion problems in Lesotho back in 1874 due to 'overpopulation and too much ploughing'.

The problems sketched above indicate that for non-temperate climatic situations the importance of tillage with respect to minimization the risk for soil degradation through soil and water conservation is at least equal to (but often higher) than the importance with respect to crop production.
Tillage constitutes the strongest and most readily available tool for the farmer, which he can use as a measure to avoid soil and land degradation.

The most obvious indicator of soil degradation is erosion. Erosion[8] as the detachment and removal of soil parts is a physical process, whereas the depletion of plant nutrients and organic material because of nonsustainable cropping and farming practices, sometimes is called 'chemical erosion' (Kayombo and Mrema, 1994). The deterioration of the nutrient status is generally the first phase of the degradation process.

Development or introduction of sustainable or ecologically sound farming does not necessarily mean that use of chemical fertilizers is to be avoided. On the contrary, in most of the semi-arid climates, soils have already undergone periods with chemical erosion, where crops are produced with very low inputs of nutrients and complete removal of all biomass produced. Here, the soil is mined and depleted of minerals such as N, P and K. In these situations, improvement of the condition of the soil is simply not possible without additions

[8] 'Soil erosion is a two-phase process consisting of the detachment of individual particles from the soil mass and their transport by erosive agents such as running water and wind. When sufficient energy is no longer available to transport the particles a third phase, deposition, occurs.' This is the description of the physical process, as given by Morgan (1995).

of fertilizer. This is particularly valid when rainfall is low or unreliable and when crop residues are not used as green manure. The west African Sahel and Savanna region is a typical example of such a situation (Penning de Vries and Djiteye, 1982).

1.5. The nature of tillage research

In agricultural research in Europe early in the 20th century it was recognized that tillage operations change the structure of the soil and kill or damage weed plants. The changed soil structure apparently was better for crop growth, but it was difficult to prove in what way. It was also observed that control of weeds increased crop yields. This gave rise to two different schools of tillage research: the English school with much emphasis on weed control as a clear effect of tillage and the German school where soil structure was studied intensively.

During the first half of the 20th century, research started to investigate effects of changes in soil structure by studying the underlying processes of soil physics and the status of water in the soil. Soil chemistry and its effect on plant nutrition was also investigated in detail.

The development of both contact- and selective herbicides minimizing the need for mechanical weed control was an important support to the research into crop production systems with a minimization of tillage activities: reduced and no-tillage systems. This research started in the 1940s in the UK and USA.

Agronomic research was primarily focussed on increasing crop yields, so producing more food per unit area. In more recent years (the 1980s in particular) there was a shift in attention (for Western, high input situations) towards an optimisation of profit per unit area. Energy flows and conservation of energy use in agriculture was an important topic during the oil crisis of the 1970s, but this was not continued after the crisis eased in the 1980s. The last decade is characterized by the concern for the environment, where agriculture was blamed for polluting ground and surface water through excessive fertilizer and pesticide applications. Agriculture is also believed to contribute significantly to global warming as a result of increased CO_2 production from agricultural fields (Lal and Kimble, 1997). The focus on these topics is reflected e.g. in the themes of conferences of ISTRO (the International Soil Tillage Research Organization; ISTRO 1988,1991,1994,1997).

The interest in sustainable agriculture is strongly related to this concern. It is recognized that application of ecological principles to agricultural production systems is a logical approach to follow. Agroecosystems, however, are quite different from natural ecosystems and research faces a challenge in guiding the evolution from an industrialised production system towards a system based on ecological principles. 'Land husbandry' or 'stewardship' as a careful management and improvement of the land resources is a term now being used by those concerned about the future of the land. Tillage is likely to play an important role in this shift in approach because of the huge consumption of (fossil) energy and/or human and animal labour, plus the fact that tillage has a strong impact on the surface condition of the soil and the vegetation present at this surface.

Although the changes in research focus towards ecologically sound farming were triggered by excessive application of power, fertilizer and other chemicals, this thought is also used as a guiding principle in agricultural research for low-input farming in developing countries in the tropics. Clearly, the current production levels are still very low and an increase of food production is the major goal, but numerous examples of depletion and degradation of the natural-resource base of agriculture by intensifying production for short-term yield increases can be given.

So although a clear shift in focus of tillage research can be seen, the nature of research has been mainly empirical. Only few attempts to linkages with e.g. modelling have been undertaken.

1.6. Modelling tillage and soil and water conservation

The advances in research of plant and soil have led to considerable in-depth knowledge of mechanisms and processes of movement of water in the soil, energy balances, nutrient movement and uptake and the growth, development and distribution of photosynthetic products in the plant as a result of development phase and environmental conditions.

The major processes could be thus be expressed in mathematical models and with the development of powerful computers, it became possible to calculate crop production based on for various soil, crop and climatic conditions, by simulating these processes in computer models.

These models proved to be valuable tools for the study of complex, weather-related processes and interactions. Compared to expensive and time-consuming field experiments, large numbers of different treatments or 'scenarios' can quickly be studied. Of course, simulation studies can never replace all field experiments, but they can indicate gaps in the knowledge of certain processes or shortcomings in the understanding of complex phenomena. Thus simulation can fine-tune the design of necessary field experiments and indicate which treatments to be included and which parameters to measure (e.g. de Wit and van Keulen, 1975; Penning de Vries and van Laar, 1982; van Keulen and Wolff, 1986).

For agronomy and soil management research in developing countries in the tropics, use of simulation models has another two very important advantages:

1. Results from agricultural field research are very few if at all available, and it is even more expensive and difficult than in the western world to initiate and carry out field experiments,
2. The climate is usually unpredictable, particularly with respect to rainfall, so field experiments will rarely yield results under the type of weather conditions allowing acceptable conclusions to be drawn. When climatic data are available, simulation modelling allows calculation of the effects of certain treatments or measures over a wide range of weather situations.

Models are developed to simulate almost any process in varying degrees of detail (scale). Tillage has an impact on different scales: it has a direct and strong effect on the structure of the soil ('tillage action' and 'operation'), but other parameters such as water movement, erosion, weed control, and crop development and yields are influenced primarily at 'tillage operation' and 'tillage system' level. Even when processes can be modelled well on one scale, the use of modelling results from a particular scale in a higher or lower one (up- or downscaling) is very difficult (de Ridder, 1997).

For the application of models within the context of this thesis where the effect of tillage on agronomic as well as on SWC aspects is assessed, there are a number of principles that should be adhered to:

a. Any model used should incorporate or be linked to a module of biomass production (a crop, pasture or natural vegetation) to see a translation of tillage effects in production under varying climatic conditions.
b. Input for the models should be relatively simple, in view of the limited availability of data and the usefulness for spatial and temporal extrapolation.

Although continuing progress is reported in model development, tillage with its direct but especially indirect effects on many parameters in the crop production mechanism, has proven to be difficult to simulate. Approaches to this subject therefore receive special attention in this thesis.

1.7. Thesis layout

In this thesis, a number of the issues and problems that were mentioned earlier are discussed. Attention is given to soils and climate the SAT, to the role of tillage with respect to SWC in these areas, and to the development and use of models in this discipline. In each of the following chapters, background and theory on above topics are treated and followed by two case studies.

In the first place, the characteristic situation of the presence of 'sealing, crusting and hardsetting' (SCH) soils under an aggressive climate with their effect on crop production and SWC is discussed. The processes underlying SCH are described. Knowledge of these processes is necessary for design/development of tillage systems. These aspects are treated in detail for two locations in West Africa: Mali (case 1) and Niger (case 2).

Secondly, a critical review (based on research findings) is given of available tillage implements and systems. Guidelines are presented for the choice of tillage operations or systems for specific situations. Methodologies on how to assess the effects of tillage of SCH soils are discussed. This is based on studies on alternative tillage systems in Brazil and on crop production effects from tillage in Niger. They are treated in cases 3 and 4 respectively.

Thirdly, the use of (computer) models as a tool for selecting tillage implements and systems or for aiding the design of new technology for specific purposes and conditions is evaluated. An overview of models representing the state-of-the-art in this field is given, including approaches of how to model tillage for SWC.
A study on the development and application of a simulation model to evaluate tillage options in the SAT is presented in case 5. In case 6, the effect of tillage on the water balance in a typical SAT situation (Mali) is assessed and evaluated using a simple model.

Finally, thoughts are given about the development of appropriate tillage systems in the SAT.

2. THE SAT: PROBLEM SOILS AND A DIFFICULT CLIMATE

2.1. Sealing, crusting and hardsetting soils in the semi-arid tropics

Soils in the semi-arid tropics can often be characterised as problem soils, i.e. soils causing problems for many types of land use, but in particular for crop production. The main phenomena which play a role here are: structural instability, poor nutrient status, poor workability. Tillage may therefore form an important factor in the management of these soils.
The most important processes (changes in structure under the influence of manipulation by the farmer or by effects of the weather or other natural causes) of these soils are sealing, crusting and hardsetting (SCH). An indication of the geographical distribution is given, followed by a more detailed treatment of these processes.

2.1.1. Global importance; geographical distribution

Africa: Van der Watt and Valentin (1992) report on a large number of research activities from West, East and South Africa. In West Africa, light soils (Alfisols), covering an important part of the agricultural production areas show severe crusting and sealing activity (Valentin, 1994; cases 1 and 2). The most dominant light soils in marginal rainfall areas of Eastern Africa are Luvisols and Acrisols, both with strong surface sealing and crusting properties (Biamah et al., 1993; Zake, 1993). In southern Africa, crusting, sealing Alfisols and hardsetting soils (Ultisols / Cambisols) are found extensively, e.g. in Botswana (Sinclair, 1987; Willcocks, 1981, 1984).
Latin America: Roth (1992) reports that problems in the SAT (northeast Brazil, Bolivia) are light. Although the actual semi-arid tropical zone of Brazil is confined to the northeast, a very large area with light 'cerrado' soils is found in the sub-humid zone. These soils generally do not have serious crusting problems. Silty soils (Alfisols and Ultisols) with sealing and crusting properties occupy important areas of semi-arid Bolivia (Gerold, 1987). Soils in the wetter parts of tropical South America are mainly Oxisols and some Ultisols.
India: According to Abrol and Katyal (1995), approx. 30% of the soils in India are red soils (Alfisols, Ultisols, Oxisols; all in association with Entisols and Inceptisols) and lateritic soils (Oxisols and Ultisols). These soils generally have a loamy sand texture, with kaolinite as the dominant clay mineral. Crusting and sealing is severe on these inert soils and the topsoil becomes very hard after a wetting-drying cycle.
Australia: Chartres (1992) and Isbell (1995) indicate that crusting problems in Australia are due to: (a) low surface organic matter contents; about 75% of the Australian soils have a median organic carbon contents of less than 1%,

and (b) sodicity; 25-30% of Australia has sodic soils (though mainly in the more temperate South, and though often only the B-horizons are sodic). Overgrazing or intensive cultivation of the soils with a combination of low organic matter and sodicity or susceptibility to dispersion due to low electrolyte concentrations leads to a considerable soil crusting problem.
Table 3 shows the areas occupied by the different soil orders.

Table 3. *Distribution of main tropical soil orders (based on Swindale, 1982).*

soil order	Africa	Latin America	Asia	Total
	% of total (100% = 21.000.000 km^2)			
Alfisols	22.3	5.1	5.8	33.2
Aridisols	21.0	1.6	2.2	24.8
Entisols	12.2	0.8	-	13.0
Inceptisols	1.8	-	1.3	3.1
Mollisols	-	3.7	-	3.7
Oxisols	9.0	-	-	9.0
Ultisols	1.1	0.4	1.0	2.5
Vertisols	2.4	-	3.8	6.2
Others	-	3.3	1.1	4.4
Total	69.8	14.9	15.2	100.0

Above information indicates that the diversity of soils in semi-arid and sub-humid tropical regions is immense (Hudson, 1987; Eswaran et al., 1992) and, although the conclusion may be drawn that a large number of the tropical soils show SCH phenomena, the currently applied soil classification systems only broadly refer to the problems associated with these soils. The SCH phenomena are a function of soil physical and chemical characteristics, and these characteristics may be widely different within the same soil (sub)groups or (sub)orders; on the other hand, soils that are classified differently may show almost similar SCH behaviour.

On a world scale, the SCH soils cover a large area. Based on the map of soil degradation by ISRIC (Oldeman et al., 1990) these soils would be falling in class Pc (physical deterioration; compaction, sealing and crusting). However, the erosion due to the runoff from the SCH soils leads to a general classification in Wt or Wd (water erosion, loss of topsoil and terrain deformation resp.) Comparing the degradation map (Fig. 2) with the SAT (Fig. 3), it is clear that the majority of the soils in the SAT is prone to water and wind erosion.

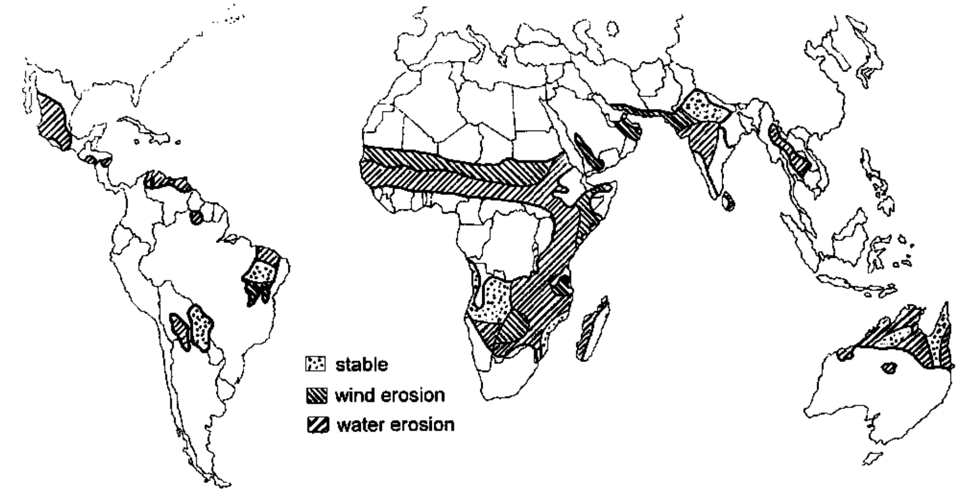

Fig. 2. *Soil degradation in the tropics (after ISRIC, Oldeman et al (1990))*

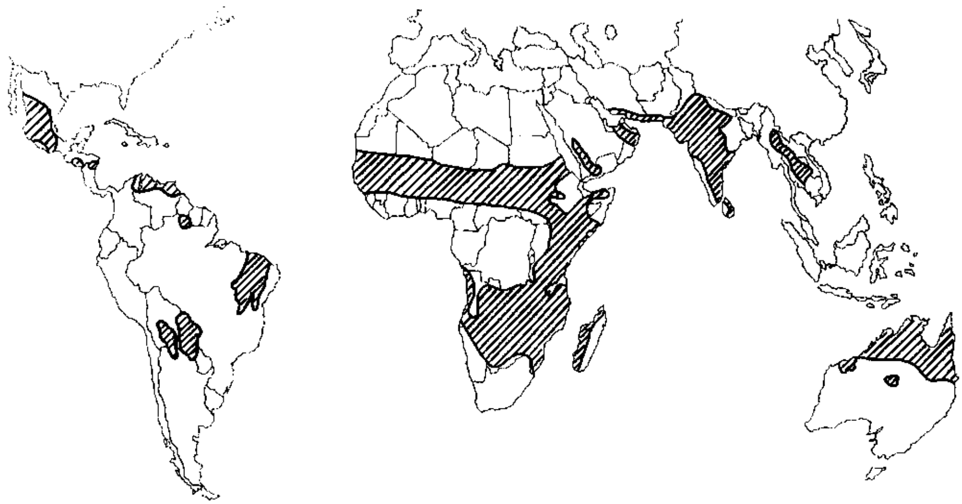

Fig. 3. *The SAT (shaded areas) according to ICRISAT (1986)*

2.1.2. Processes and factors in SCH formation

Definitions

The following descriptions are generally accepted, as a result of an exhaustive treatment of this subject in conferences held in Gent, Belgium (Callebaut et al., 1986), Athens, USA (Sumner and Stewart, 1992) and Brisbane, Australia (So et al., 1995) and in other special publications (such as Cary and Evans, 1974)

Sealing: Seals are very thin (less than 2 mm) layers of soil material which are characterised by a greater density, finer pores and lower saturated hydraulic conductivity than the underlying soil. This layer may be formed by aggregate breakdown at the surface, deposition of clay after suspension by (rain)water etc. In all cases, the seal is wet.

Crusting: Crusts are superficial soil layers (up to 5 cm thick), characterised by few large pores, a high bulk density, but also by stratification, platiness, and orientation of the different sized materials. A crust is dry, and as such, it is hard (high shear strength) and therefore difficult to penetrate (e.g. by seedlings).

Hardsetting: A process found in 'Structurally unstable soils which lose strength and see a collapse of macropores during wetting. When the whole (A_1) horizon is affected, these soils set to a hard, structureless mass during drying and are thereafter difficult or impossible to cultivate until the profile is rewetted' (Mullins et al., 1990). The hardset soil shows a high degree of mechanical impedance to roots, there is a lack of structural units, the soil does not develop structural cracks on drying (Young et al., 1991; Young, 1992). This soil type shows a narrow range of friability and workability[9].

Formation

Sealing and crusting are indicators of processes which to a large extent are similar or at least comparable: slaking, aggregate destruction, formation of disrupted, low-porosity layers etc.

Sealing is considered to be a physical process where raindrops cause a 'disruption' of the structure of the soil immediately at the surface. Following this description, a seal is a very thin layer at the soil surface or at a depth of not more than equalling the diameter of one aggregate in an aggregated soil, or the size of sandgrains in a sandy, non-structured soil.

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[9] Friability: the ease of crumbling of soils. Workability (or tillability): the degree or ease by which a soil may be manipulated for a specific purpose.

A seal is formed by the kinetic energy of a falling water drop. On fine sandy soils, the impact of the raindrop separates clay and silt particles from the larger sand grains. Clay and silt particles are then transported by the infiltrating water and during this process, they clog the pores. This clogging of the (small) pores may very effectively reduce the infiltration of water through this layer. It implies that the actual, effective thickness may be a few times the size of the silt particles.
When the seal is formed on an aggregated soil, the thickness of the layer reducing the infiltration will be thicker because of the larger pores between particles. This process may end up in a situation where a seal is overlying a thicker crust.

Thus, for light soils, so with a clay content of less than approx. 10%, the difference in sealing tendency is most likely explained by the textural difference; as an example data from a soil survey in Northwestern Nigeria (Sombroek and Zonneveld, 1971) were used to relate sealing with particle size distribution. Characteristics of a number of comparable soils are given in Table 4. Strongly sealing soils show a relatively high percentage of silt and very fine sand and are only moderately sorted, whereas the non-sealing soils are better sorted and contain less silt or very fine sand.

Table 4. *Texture vs. sealing characteristics (based on Sombroek and Zonneveld, 1971).*

soil	clay* (%)	silt (%)	very fine (%)	fine sand (%)	medium sand (%)	coarse sand (%)	sorting **	sealing
Sangiwa***	8	6	15	37	24	10	66	severe
Zurmi	9	5	24	43	12	7	74	yes, less than S
Sokota	10	3	10	43	28	6	79	no
Illela	6	1	7	44	34	8	83	no
Mali (case 1, 6)	5	13	34	25	19	4	62	severe
Niger (case 2, 4)	3	5	15	34	33	10	69	some

* Clay: <0.002 mm; silt(loam) 0.002-0.05 mm, very fine sand 0.05-0.1 mm, fine sand 0.1-0.25 mm, medium sand 0.25-0.5 mm, coarse sand > 0.5 mm

** The two highest (adjacent) sand fractions as percentage of all particles > .002 mm

*** The first four soils are from Nigeria

In soils with a finer texture (clay percentage roughly between 12 and 20%), the nature of the clay minerals plays an important role in seal formation. Non-swelling and shrinking clay minerals (such as kaolinite) cause compact soils and thus may initiate sealing, but the presence of smectite in kaolinitic soils apparently is able to trigger a strong dispersion and thus to a more serious seal formation (Stern et al., 1991).

Crusting: In addition to aforementioned conference proceedings, causes and formation mechanisms of various types of crusts and their effects have been investigated and reported by authors as Goyal (1982) and Casenave and Valentin (1989).
In crust formation, the mechanical mechanisms (slaking, structural collapse) and chemical mechanisms are complementary. Due to wetting, raindrop action, tillage or traffic, there will be a breakdown of aggregates and stirring of soil particles. The stirring of soil particles enhances the rate of chemical dispersion (Shainberg, 1992).
Seal formation on a freshly cultivated soil begins with the breakdown of surface clods and aggregates by both physical and chemical dispersive forces (Sumner, 1994). The physical processes are controlled by the magnitude of mechanical forces produced by raindrop impact and by air escaping from the aggregates in relation to the internal resistance of the aggregates. Problems with crusting are often more severe when rain falls on a dry soil compared to the situation when rain falls on a wet soil. The slaking as a result of sudden wetting of dry aggregates is more intensive due to air explosion.
The extent of chemical dispersion is determined by the chemistry of the pore water and eroding fluid. (Bradford and Huang, 1992).
Sumner (1994) distinguishes four types of crusts, found in various locations of the world:
(a) *Chemical crusts* composed of salt encrustations commonly found in arid soils and capable of reducing infiltration,
(b) *Structural crusts* formed by raindrop impact and clay dispersion occurring over wide ranges of soil type,
(c) *Depositional or sedimentary crusts*, formed by transport and deposition of suspended material, and
(d) *Cryptogamic crusts* formed by organisms such as algae, mosses and lichens growing on the soil surface.

The structural crusts and depositional or sedimentary crusts are largest in area as well as in agronomic importance. Casenave and Valentin (1989) have published a detailed report on these two types of crusts as found in West Africa.

West et al. (1992) have proposed a simple model for surface crust development, assuming an aggregated surface soil which is subjected to rainfall. Raindrop impact and slaking will cause breakdown of aggregates and particle rearrangement. A 'disruptional' layer is formed with reduced porosity compared to the underlying soil. The kind of processes in a following stage depend on the dispersibility of the soil material. A high dispersibility will lead to more particle disjunction and this fine material will form a washed-in layer, further clogging up the disruptional layer. This process does not occur with low dispersibility. Here the disruptional layer becomes thicker and fine material is removed by runoff. A final stage shows removal of fine 'washed-out' material from the top of the disruptional layer by runoff water. So in the end the low-porosity layers are exposed to the surface, where for the low dispersible clays the layer is thicker but consisting of more 'undisturbed' aggregates and for the high dispersible clays a thinner (smoother) layer which has a lower porosity.

Dispersibility of the clay fraction apparently is an important factor. In well aggregated soils, organic matter and sesquioxides bind clay and other particles into water stable configurations which resist the energy of impacting raindrops. When the binding elements are lost, which is particularly the case with a decrease of organic matter content as a result of farming in the SAT, the aggregates are more vulnerable to the applied energy. So and Cook (1993) showed that the degree of crust formation may be predicted by determination of the amount of dispersed clay after slaking, which is a function of clay content and the amount of exchangeable sodium (ESP).

In aggregated soils, clods (>20mm) present at the soil surface do not act as cover units such as crop residue etc., but do delay the development of a crust. Clods provide a source of finer aggregates for the development of a crust. Under these conditions, Freebairn et al. (1991) state that loss of aggregate strength and raindrop detachment act as a built-in feedback: where crust formation occurs, splash erosion is decreased, producing a more stable surface.
Depressions (such as those made by basin tillage) have little influence on total infiltration. A possible increase in infiltration rate (due to a larger hydraulic head of the ponding water) is generally offset by a thicker depositional crust at the bottom of the basins.

Summarizing, crust formation thus is different from seal formation on two important points:

(a) a seal can be formed even on very light soils with small amounts of clay and silt, with the dispersibility of the clay playing a less important role since seal formation is a physical process
(b) the energy of the rainfall is crucial: a certain minimum energy is needed to arrive at the actual separation of clay/silt from the larger grains or structural units

Hardsetting: Mullins et al. (1990) have indicated the range of textures in which soils may be expected to show hardsetting behaviour. A wide range of

textures from loamy sand up to (sandy) clay may fall in this category, with the condition that the clay minerals should not be swelling and shrinking types. So this listing excludes the very sandy soils and heavier (cracking) clays.
Soils with a high amount of cementing agents like iron- and aluminum oxides, like lateritic type soils, may also show hardsetting behaviour, even when these oxides are found in sandy soils as is the case in West Africa. Organic matter content is always low in hardsetting soils. This is particularly so for soils under (continuous) cultivation in the semi-arid tropics.
The major processes initiating hardsetting are slaking or slumping (the disintegration of aggregates during wetting) and the subsequent compaction without the application of an external load. The more abrupt and intense the wetting process, the higher the degree of slumping or loss of porosity. Wetting of aggregates under tension will cause a smaller loss of porosity than wetting at saturation. Air-dry aggregates will disintegrate easier (air-explosion) than moist aggregates.
In the first stages of drying after the wetting process, uniaxial shrinkage may occur. During the entire drying process, there is a sharp increase in the strength of the hardsetting soil.
The depth of the layer of the soil where hard setting occurs, is at least that of the tilled layer. Usually, however, the soil under the tilled layer has been subjected to many more drying and wetting cycles without seasonal loosening, so the phenomena of reduced porosity and high strength will be found in deeper layers as well.

Surface densification, as described by Bedaiwy and Rolston (1993) can be considered as an intermediate form between hardsetting and crusting. This is an extension (in depth) of a consolidated layer, below a crust formed under intensive rainfall. The depth of this layer was found to be strongly related to rainfall duration, in experiments done on a loam soil.

Clay bands may be found below a washed-out layer in light (sandy) soils (Bielders and Baveye, 1995): through the occurrence of shear strain in the first mm of a crust during rainfall, there is a temporary change in pore size allowing preferential downward movement of finer grains. This process does not result in a hardset layer, but the clay bands may reduce vertical water movement.

2.1.3. Properties of seals, crusts and hardset soils that influence agricultural production.

Reduction of (rain)water infiltration and generation of runoff

The actual reduction of the infiltration rate through sealed and crusted surfaces may be enormous: final infiltration rates may decrease in one rain storm from an initial rate of 100 mm h^{-1} or higher down to a value of 10-15 mm h^{-1} (as e.g. shown in cases 1 and 6, and by Sivakumar (1989)). Losses in the order of 50 to 90 % of the volume of rainshowers are not uncommon and will severely influence the water balance. Sinclair (1987) reports runoff up to 50% on Alfisols with slopes less than 5% in Botswana. Similar figures and higher are found for the Sahel area (e.g. Casenave and Valentin, 1989).

Erosion by water

As a result of reduced infiltration and increased runoff, the water running off a slope may become erosive depending on velocity and quantity of the water. The detachment of soil particles by the impact of raindrops is considerable since the sealing and crusting processes are caused by the instability of the soil (aggregates) at the surface. Erosion thus is a serious problem (Pieri, 1989; Roose, 1984; Kemper and Derpsch, 1981). Soil degradation is generally seen as a result of erosion processes, but the underlying phenomena may be the sealing and crusting behaviour of the soil.

Erosion by wind

The resulting seals and crusts at the surface of these soils generally give a certain protection to the erosive forces of the wind. Wind erosion, therefore, is a relatively small problem, but on the formation of a seal and crust and connected processes, a certain separation of particles of different size is observed. Typically, loose sand grains may be found on a sealed or crusted soil surface. These particles are prone to wind erosion. Also, when the crust is very thin, a small area where it is damaged may initiate detachment by the wind and wind erosion may be serious.

Seedling emergence

Seedling emergence restrictions are often found on crusting and hardsetting soils. On sealing soils, the restricting layer is only thin, and emergence generally is not a problem. An extensive review on the magnitude of the problem and the impact on emergence of various crops was given by Goyal (1982).

Problems are reported by Roth (1992) for South America, Goyal (1982) for the USA, Rathore et al. (1983) and Abrol and Katyal (1995) for India, by Willcocks (1981) and Zake (1993) for southern and eastern Africa and Valentin (1993) for West Africa. Quantitative data are scarce. In general, crops with large, strong seeds (maize, beans, groundnut) will have few problems. In West Africa, the fine-grained sorghums and millets often have problems (case 2 and 4). In Brazil, emergence of soybean or wheat generally is not a problem (case 3).

Clearly the most serious harm done by crusting comes from a situation where heavy rainfall falls on a freshly sown field with a finely aggregated or structureless seedbed.
On very light soils, newly emerged seedlings may be seriously damaged (up to a complete destruction of the plants) by sandblasting, movement due to high windspeeds of fine sand particles just above the soil surface. Solutions to this problem are treated in case 2.

Agricultural productivity

This factor is a function of many biotic and abiotic factors. The relationship with SCH phenomena is not unique but indirect, in particular through the influence on the waterbalance and crop and root development. It is impossible to give an exhaustive treatment of this subject here, but productivity (yield) aspects are found in all cases following.

Effect on (natural) vegetation

All aforementioned effects of SCH on an agricultural crop do also apply on natural vegetation but the actual production of biomass will not always be influenced negatively. Often, situations may occur where the total amount of rainfall, when uniformly infiltrated into the soil profile, may not be sufficient for generating an minimal development of natural vegetation, thus yielding no or useless amounts of biomass. When under such climatic conditions crusted and sealed spots cause a considerable spatial redistribution of water (runoff zones vs. runon zones), then elevated biomass production may be found, be it on part of the area only. A typical example is 'tiger bush' as described e.g. by Casenave and Valentin (1989). Many water harvesting techniques apply the same process artificially (Boers, 1994).

Energy and machinery requirements

SCH soils are more difficult to till (manipulate) than well-structured soils. There will be a *higher energy demand* and a *narrower workability* range of these soils. In 3, these problems will be discussed.

2.1.4. Organic matter and biological activity

Organic matter

Organic matter plays a key role in influencing characteristics of soils. On clay soils higher percentages of SOM lead to a better friability, in sandy soils the presence of SOM prevents the formation of a massive, hardset structure. In many studies carried out in a.o. West Africa and Brazil (Feller and Beare,

1997) it was shown that there is a clear relationship between total SOM and e.g. aggregation stability, although it is understood that the effect varies between different families of organic compounds. Amounts of SOM were found to be related to the texture expressed as silt plus clay (all particles < 20 µm) content.
This implies that the poor structural status of many light West African soils is only partly explained by the soil texture, characterized by a low percentage of clay, (which is non-swelling and shrinking), but for a great deal can be attributed to low organic matter contents. Feller (1979) distinguishes the following forms according to the size of the parts: > 2 mm: large-size vegetation residue (straw, roots, grains); 0.2 - 2 mm residue still visible with the naked eye (small seeds, roots); 0.05 - 0.2 mm: material hardly discernible, vegetative and excretions, already decaying; < 0.05 mm: humus in its strict sense.
SOM content of SAT soils under crop production is low: in West Africa typical values range from 0.2 to 1.0 %[10]. The positive effect of organic matter is commonly recognised: SOM has a positive effect on the aggregate stability of the arable layer (Dutartre et al., 1993) and can help in stabilising the surface of a structureless sandy soil (case 2). These effects also become apparent in the reduction of runoff losses under rainfall on fields with a higher SOM, as found in Burkina Faso (Hoogmoed et al., 1999). It is very difficult, however, to keep up sufficiently high levels of SOM under tropical conditions.
Applying the equation $C\% = 0.032\cdot(\%silt+clay) + 0.087$, as proposed by Feller (1995), for threshold SOM values to allow sustainable annual cropping, would yield for the Mali soil (case 1 and 6) 0.66 %C, and for the Niger soil (case 2 and 4) 0.34 %C. In both situations, values measured were well below these thresholds. Annual relative decomposition rates are in the order of 0.06, which is roughly 1000 kg OM per ha (assuming an arable layer of 20 cm with a bulk density of 1.5 g cm^{-3}), so increasing the SOM percentage will require huge amounts of straw and even more animal manure or compost (de Ridder and van Keulen, 1990).

Soil tillage and crop production have a decreasing effect on the SOM content. Feller and Beare (1997) showed clear differences in the relationship between SOM and silt plus clay for situations with and without cultivation.
The precise role of tillage on SOM content, however, is not fully understood: clearly loosening of soil will increase the aeration, so oxidation of organic material is increased. On the other hand, the burying of material will cause a protection to the direct influence of the weather.

In Paraná, Brazil SOM content decreased by 50% over roughly 10 years of

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[10] A factor 2% SOM = 1% C may be applied (Nelson and Sommers, 1982)

crop production, after clearing virgin forest, from approx. 4% C to 2% C under no-till and 1.6% C under conventional tillage. This decrease continues at a slower rate under conventional tillage, but stopped when no-tillage or a system with cover and green manure crops was applied (Roth et al., 1992).

Biological activity

Although all kinds of burrowing animals will have a certain effect on soil surface characteristics, termites, ants and earthworms are the most important in influencing soil surface hydraulic behaviour. Cogle et al. (1995) indicated the positive effects through an increased aggregate stability and the development of surface connecting macropores.

Termites are the most important soil fauna in the drier tropics. Many species of termites forage on (usually dead) organic material. Due to their nesting behaviour and their sensitivity to daylight, large amounts of soil material are moved, particularly near the surface layer. So on a micro scale, they perform a tillage operation by opening up the soil. Farmers often make use of this activity by spreading straw on poor or degraded spots in the field. Mando (1997) found in studying termite effects in Burkina Faso that spreading a mixture of woody material and straw triggered the activity of termites. This caused a disruption of the crusted surface and resulted in a strong reduction of losses of rainwater as runoff. There is, however a strong interaction between the physical effects of the mulch layer and the termite activity.
On the other hand, termites can also be responsible for impermeable layers at the surface when excretions of the termites are mixed with soil in order to stabilise mounds, and where clay from deeper layers is brought to the surface etc. The infiltration rate may drop to very low values in the immediate vicinity of usually abandoned termite mounds. This effect will be permanent if no mechanical loosening is performed (Hoogmoed et al., 1992).
Ants are quite similar in their effect on the hydrology in that they also utilise only few large surface opening pores (Cogle et al., 1995).
Earthworms are important because they create vertical channels near the soil surface. These channels, however, should be open to the surface in order to improve infiltration. Earthworms are not found in very dry regions, but in climatic regions such as the moist West African Savanna (with annual rainfall > 800 mm), earthworms are often the dominant group of soil macrofauna (Lal, 1987, 1988; Lavelle, 1988). The activity of earthworms is often the key to a successful application of the no-tillage system: in Brazil, in the experimental site described in case 3, numbers showed a 5 to 8-fold increase 1½ years after a shift from conventional tillage to no-tillage (Kemper and Derpsch, 1981).

2.2. Climate characteristics

2.2.1. Temperature, radiation, wind

An example of temperature characteristics for West Africa is given in figure 5, where temperature and radiation data for Niono (Mali) are given. Air temperatures reach a maximum in April-May, with maximum values of over 40 °C. Daily minima never fall below 20 °C during that period. December and January are the coldest months with maxima of 25 °C and minima of 8-10 °C. During the growing period daily maxima are 30-32 °C. Solar intensity reaches 1 kW m^{-2} at noon under clear skies. This level does not vary much during the year, although clouds in the rainy period will decrease these values.
Wind speeds are high in the first months of the year (January-March, so-called "Harmattan" winds), but low near the end of the rainy season. During rainstorms, however, windspeeds may reach very high values, which contributes to the impact-force of the raindrops.
The resulting potential evaporation is very high in the dry period, particularly in the period March-May. Class A evaporation pan values of 10 mm day^{-1} can be observed.

For the Brazilian site (case 3), average maximum temperatures range from 30 °C in the summer period of October-March with peaks to 37 °C, and minima of 15-20 °C. In the cold months May-August, maxima are around 25 °C, and minima of 10-12 °C, with occasional nightfrost risk.
Radiation levels are slightly lower than West Africa due to latitude, with dips in sunshine hours during the rainy period (particularly October and December-January). Windspeeds are moderate.

2.2.2. Rainfall

When studying the hardsetting process and the formation of seals and crusts (cf. 2.1.2), the role of rainfall is obvious. Rainfall can be characterized in various ways, ranging from total precipitation in a year, season or other period, down to daily rainfall or totals per rainfall event. The most detailed analysis of rainfall is a breakdown of the rainfall event by measuring the intensity in time. In addition, information on drop size and fall velocity of the drops will be needed in determining the energy generated by the falling rain.

Energy

For sealing soils, the kinetic energy of a falling raindrop is the major cause of changes to the soil structure in the surface layer. The kinetic energy is a function of fall velocity and volume/weight/shape of the falling raindrop at the moment of hitting the soil surface. Tropical rains generally have larger size drops than rains developing in temperate regions, so experimental results are not simply interchangeable (e.g. Hudson, 1971). It was found that kinetic energy can be related to the intensity of the rainfall, and thus an intensity analysis will provide quantitative information on the aggressiveness of the rain. This aspect will be treated in detail in case 1.

Although annual rainfall in Paraná, Brazil (case 3) is higher than in the study region in West Africa, rainfall in the critical period of seedbed preparation in Brazil was found to have intensities comparable to West Africa (Hoogmoed, 1982).

Seasonal distribution of rainfall

The importance of rainfall providing water for seed germination, and plant establishment is obvious. Long dry spells, particularly in the situation with soils with a low water holding capacity, may cause serious reductions in plant growth and yields. Apart from the agronomic importance, the rainfall distribution is also very important for soil and water conservation processes. The condition and shape of the soil surface at the moment of rainfall, will dictate the effect of rain. Rain hitting a layer of air-dry aggregates may cause air-explosion of aggregates under rapid wetting and subsequent sealing of the soil surface layer, although on the other hand infiltration may be increased by the dry soil. In the situation of rainfall when the soil is wet already, a seal may be present and due to a lower pressure potential, infiltration rate will be smaller, possibly leading to increased runoff. This does not necessarily need to lead to more erosion, there will be a better stability of the crusted soil surface.
Rainfall distribution will also influence strongly the number of workable days. The narrow workable range of the SCH soils will lead to very few workable periods when dry periods are too short in the beginning of the rainy period.
Repeated wetting and drying cycles of the soil will also lead to increased strength of the soil (Mullins et al., 1990).

2.3. Case 1: Crust formation on sandy soils in the Sahel: rainfall and infiltration

2.3.1. Introduction

The Sahel area has a semi-arid climate characterized by average annual rainfall limits (isohyets) of 100 mm $year^{-1}$ in the north to 600 mm $year^{-1}$ in the south (Fig. 4).

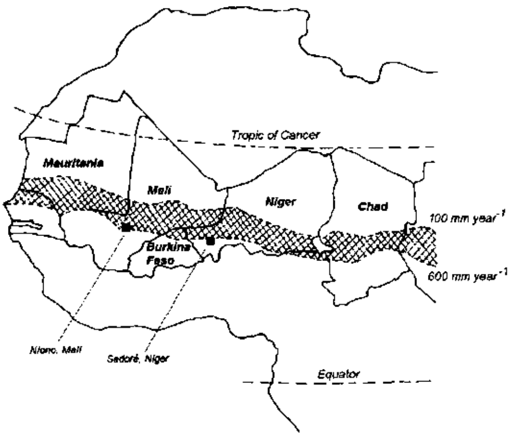


Fig. 4. *The Sahel zone in West Africa.*

There is a short, wet summer period with a one-peak rainfall distribution and a prolonged dry period (Fig. 5). Air temperature, humidity, wind speed and irradiation do not differ significantly from one year to another (Fig. 6). As a result, the potential evapotranspiration is a rather conservative quantity, showing a pronounced drop during the (rainy) growing season (Fig. 7).

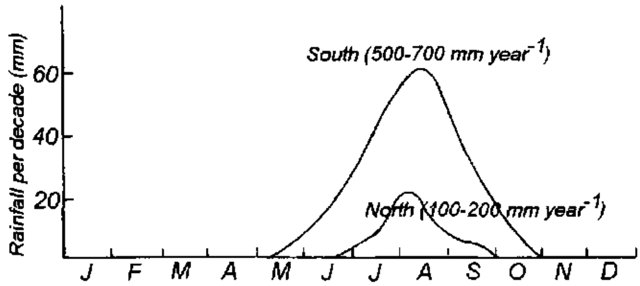


Fig. 5. *Average rainfall distribution for the north and south limits of the Sahel zone (after Davy et al., 1976).*

The natural vegetation is in accordance with rainfall, soil type and topography, mainly via the soil moisture regime (Breman and Stroosnijder, 1982). Consequently, the growing cycles of natural species vary from 10-30 days in the north and from 20-80 days in the south. On the average, the area occupied by trees varies from 10% in the south to less than 5% in the north. However, these averages contain extremes, from abundance in depressions to average on dune slopes to nil on the larger clay plains. The open Sahel vegetation is dominated by annual species. Fast germinating grasses of the C4-photosynthetic type predominate over slow germinating dicotyles of the C3-photosynthetic type. On the average only 5% of the biomass consists of leguminous annual species.

Table 5. *Data of a typical southern Sahelian soil in Mali for millet growing.*

Particle size analysis (%, w/w)			*Chemical characteristics*	
Clay (<2 am)		5	pH water	6.0
Fine loam (2-16 μm)		5	pH KCl	4.5
Coarse loam (16-50 μm)		10	C (%, w/w)	0.25
Very fine sand (50-105 μm)		35	N (%, w/w)	0.025
Fine sand (105-210 μm		25	C/N	10
Medium coarse sand (>210 μm)		20	EC (1:5) (mmho/cm at 25° C)	0.03
			Total P (μg/g)	100
Classification			P-Bray II (μg/g)	4
Textural	: Loamy fine sand		K (μg/g)	80
USA Soil Taxonomy	: Ultic Haptustalf		Fe_2O_3 (%, w/w)	0.87
FAO/UNESCO World	: Eutric Nitosol		CEC (pH 7) (me/100 g)	2.0
French system	: Sols ferralitiques		Na (% CEC)	-
Local name	: Séno		K (% CEC)	10
			Ca (% CEC)	60
			Mg (% CEC)	30
			Base saturation (%)	100
Soil structure			CEC (me/100 g clay)	40
Bulk density	at 5 cm depth	1650		
(kg m^{-3})	at 15 cm depth	1550		
	at 25 cm depth	1450		
Moisture content at pF 2.0 (%, v/v)		21.0		

Arable crops can be grown in the south of the Sahel only. At the 400-mm isohyet the risk of crop failure is very high and cropping is already marginal. Exceptions are depressions and temporary dry river beds. Millet *(Pennisetum glaucum (L.) R.Br.)* is the major cereal crop. Short-season varieties need a minimum growing cycle of 75-100 days in order to give a grain harvest. Sorghum (*Sorghum bicolor*), an important cereal crop of the Savanna area, is grown in the Sahel only in depressions. Groundnut *(Arachis hypogea)* is the major cash crop but also forms an important part of the diet of the local population, the crop residue being valuable as cattle feed. Cowpea *(Vigna sinensis)* is the major grain legume crop, serving as a food and a cash crop. The main cropping system is inter-cropping; there is hardly any sole cropping.

During four years of field work in Mali it was frequently observed that runoff starts very soon after the beginning of a rainstorm, even on sandy soils. Obviously, this is due to the very high rainfall intensity and, on most soils, to the presence of a surface crust. Crust characteristics and infiltration, runoff, evaporation and transpiration were studied for natural pastures in a multidisciplinary research program (Penning de Vries and Djitèye, 1982). It was concluded that in the southern part of the Sahel nutrient shortage is the major production limiting factor for the natural vegetation and not, as one might think, water shortage. However, in the south of the Sahel (>400 mm rain per year) sandy and loamy soils are not only used as pasture for extensive grazing but also for growing arable crops, mainly millet (*Pennisetum glaucum (L.) R.Br.)*. Since the growing cycles of these arable crops are longer than those of natural species, water shortage due to runoff and impeded infiltration can be a more important factor for arable crops than it is for the natural pastures. Thus a special study was made of the mechanism of crust formation, rainfall characteristics and water infiltration.

2.3.2. Materials and methods

Rainfall analysis

The sandy soils of the Sahel zone tend to become very hard and compacted during the dry season, so with the limited energy sources available (animal or human power), the farmer is forced to delay ploughing until the rain has wetted the soil to a sufficient depth. Crop growth in these regions is determined less by average rainfall than by the actual rainfall distribution in a specific year. Therefore, in the analysis, rains were divided into 3 size classes: small (<10 mm), medium (10-20 mm) and large (>20 mm). For the analysis of the Mali rainfall, observations over three years (1977-1979) were available. Charts of recording rain gauges were analysed through a computer program (Morin and Jarosch, 1977), in which each storm is divided into segments of equal intensity. The distribution of intensity-classes can thus be assessed. For 1977, 29 storms (a total of 376 mm rain) measured at one location near Niono were analysed. For 1978 and 1979, at 6 locations near Niono, 186 and 212 storms with a total rainfall of 1984 and 2408 mm, respectively, were analysed.

The kinetic energy E of a rainstorm is a good indicator of the erosive 'power' or erosivity of the rainstorm. According to Wischmeier and Smith (1978):

$E = 210.3 + 89.0 \log I$,

in which E is kinetic energy ($J\ m^{-1}\ mm^{-1}$) and I is the rainfall intensity ($mm\ h^{-1}$). However, rainfall characteristics in Africa are different from the U.S.A., and Hudson (1971) found for East Africa a better correlation between rainfall erosivity and E, when E was calculated only for $I > 25\ mm\ h^{-1}$ (the E>25 index). Lal (1976) proposed for Nigeria an even simpler erosivity index, the AI_m, index, in which A is total rainfall (cm) and I_m is maximum intensity ($mm\ h^{-1}$). This index is in fact a weighted mean intensity of the rain. These three indices were used to assess and compare rainfall characteristics from different locations.

Crust formation

On many soils in the semi-arid zone, crust formation is a well-known phenomenon. Depending on the soil type, two types of crusts may be distinguished:

1. A crust which is hardly noticeable, with an effective thickness of no more than about 0.1 mm (Fig. 9). This crust does not impede seedling emergence, but seriously impedes infiltration. It is observed on fine sandy soils with only a small percentage of clay or silt (5% of particles <50 µm). The impact of raindrops separates clay and silt particles which are then transported by the infiltrating water (suction by the unsaturated subsurface layers). This process, during which the particles clog up the pores in between the sand grains, is described in detail by Chen et al. (1980).

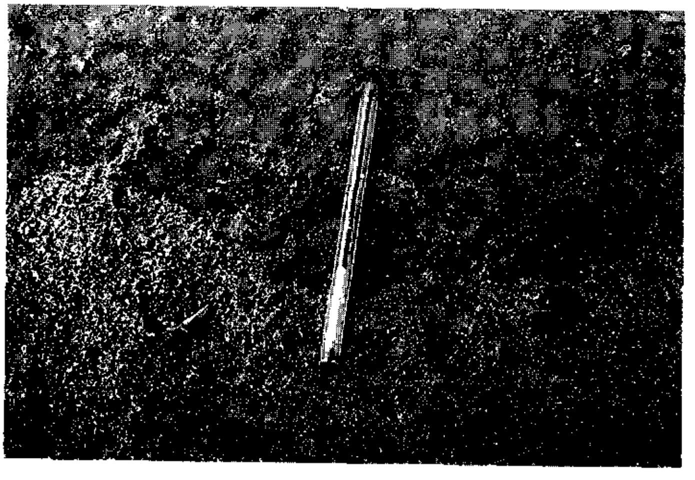
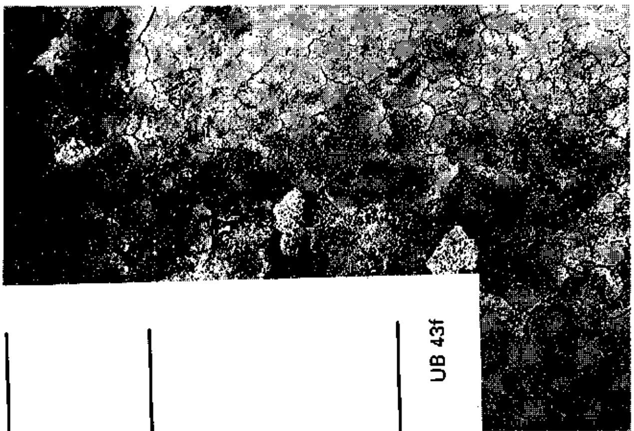


Fig. 9. *Example of a crust on a sandy soil with only a few percent loam. Texture fractions are separated under the high kinetic impact of the rain; the finer fraction is sucked into the underlying pores by the infiltrating water. Coarse sand grains (bottom) become isolated on top of the crust and may be blown by wind.*

2. A crust which is easily visible, with a thickness of at least a few mm, is created by the destruction of aggregates by immersion or direct raindrop impact (Fig. 10). In a wet state, the crust will reduce infiltration and, when dry, form a barrier against seedling emergence. This type of crust is formed on aggregated (loamy, clayey) soils.



ılar structure of the crust is
a crust, air cannot escape
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e infiltration characteristics

e clearly of the very thin,
meability, this crust has
...ng hydrophobic character (Stroosnijder, 1977). The hydrophoby is at the

surface of the thin crust only and is caused by the presence of soil algae *(Cyanophyceae)*. However, in laboratory experiments, Rietveld (1978), using the soil described in Table 5, found that physical crust resistance is of far higher importance to infiltration than the hydrophoby. It was shown that the repellency of the hydrophobic part of the crust disappeared within 5 min after rain started.

Infiltration rate

In 1979, a nozzle type rainfall simulator was used (Figs. 11 and 12), which was built after Morin et al. (1967) and Rawitz et al. (1972). In this simulator, drops are formed by pumping water through a nozzle with a large opening to obtain drops of a proper size and with an acceptable terminal velocity. Immediately under the nozzle a rotating disc intercepts all water from the nozzle except for a small part which passes through a radial segment cut out of the disc. By using discs with different openings, the intensity of the rain can be changed.
All excess water, intercepted by the disc is collected in a circular pan, surrounding the disc and returned to the storage tank. Water is pumped by a small electric pump to the nozzle, while disc and nozzle are rotated by a small electric motor. In the field, electricity is obtained from a gasoline-powered generator.

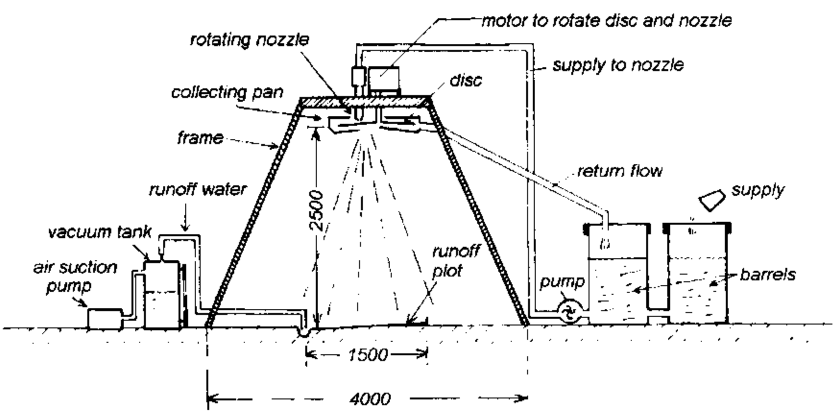


Fig. 12. *Schematic of the rainfall simulator used in Mali to measure infiltration and runoff of crusted sandy soils. Dimensions: mm.*

The rain from the simulator covers a circular area with a diameter of about 3 m. Within this area, an infiltration/runoff plot of 1.5 x 1.5 m^2 is situated. By means of neutron probe measurements during natural rainstorms in the field (Stroosnijder and Koné, 1982), it was assessed that the limited size of these plots does not influence the infiltration rate.

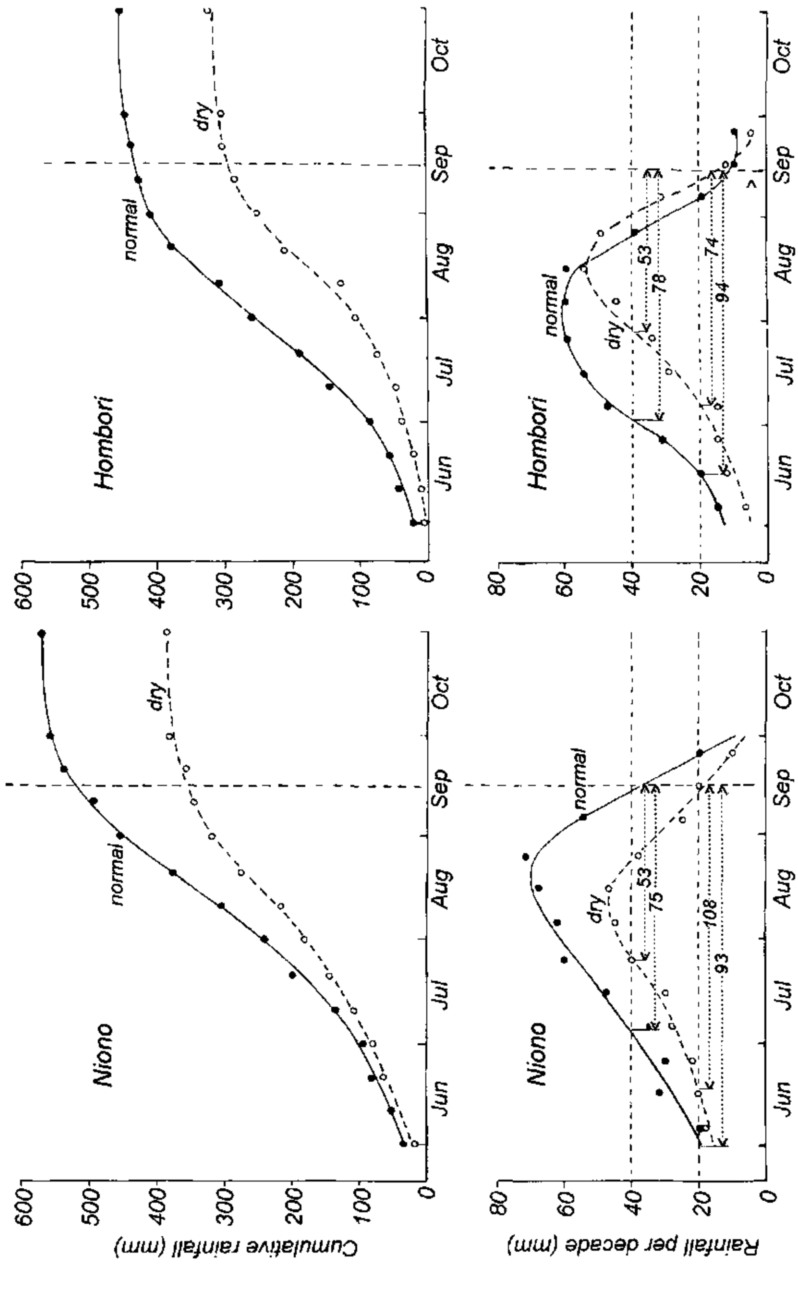


Fig. 13. *Cumulative rainfall and rainfall per decade at Niono (14 °15' N) and at Hombori (15 °17' N).*

Since the artificial rain also falls outside the plot area, there is no horizontal flow of water in the soil within the plots. Hence it was sufficient to border the plot with steel strips pressed or hammered into the soil to a depth of only 5 cm. Within the plots the soil surface should be sloping; at the lowest part of the plot a trough is placed to collect the runoff water and to transport it to a small bin, from which it is pumped to a calibrated container. The level in the calibrated container is recorded at fixed intervals and thus the runoff rate can be calculated. The intensity of the artificial rainfall was kept at a constant rate of 49 mm h^{-1}. The infiltration rate is the difference between rainfall rate and runoff rate. On the sandy soil described above, 40 simulated rainfall/runoff measurements were made (Hoogmoed, 1981). Experiments were carried out on undisturbed soils, on soils where the crust was carefully removed by hand and on ploughed and ridged soils.

2.3.3. Results

Rainfall analysis

Fig. 13 gives averages for the cumulative rainfall and the rainfall per decade for a 'normal' year and a 'dry' year for two locations in Mali: Niono (14° 15' N) at the southern border of the Sahel; and Hombori (15° 17' N) almost at the northern border of the millet growing area of the Sahel. The 50% and 90% probability values (Fig. 8) for Niono are 470 and 290 mm $year^{-1}$ and for Hombori are 365 and 250 mm $year^{-1}$, respectively. For Niono, the 'normal' year curve (Fig. 13) is the average over 1957, 1959, 1962 and 1975. These years had their total rainfall in the period July-September closest to the 50% probability value of a series of 30 years (1950-1980). The 'dry' years 1966, 1972, 1973 and 1974 had rainfall in the same period closest to the 90% probability values. For Hombori, the 'normal' year curve is averaged over 1924, 1942, 1953 and 1962; the 'dry' year curve is averaged over 1941, 1946, 1949 and 1959 (observation period 1923-1965). Although average annual rainfall for the locations differ by more than 160 mm, in a 'normal' year this difference is only 105 mm and in a 'dry' year only 40 mm for the important part of the season. The lower part of Fig. 13 shows how long the growing season will be if a minimum precipitation per decade is set. For instance, if the lower limit is set at 40 mm $decade^{-1}$, a quantity necessary to start growth if one accounts for 50% runoff (see case 6), the period up to 15 September (general flowering date due to photoperiod) will be 75 or 50 days for a 'normal' and a 'dry' year, respectively, for both Niono and Hombori. However, if a lower limit of 20 mm $decade^{-1}$ is set, a quantity sufficient for growth if runoff is nil, this period will be 105 and 90 days for a 'normal' year and 90 and 70 days for a 'dry' year, for Niono and Hombori respectively.
Fig. 14 shows the actual rainfall distribution at Niono for 1976-1979, which clearly demonstrates the large differences in rainfall pattern early in the season.

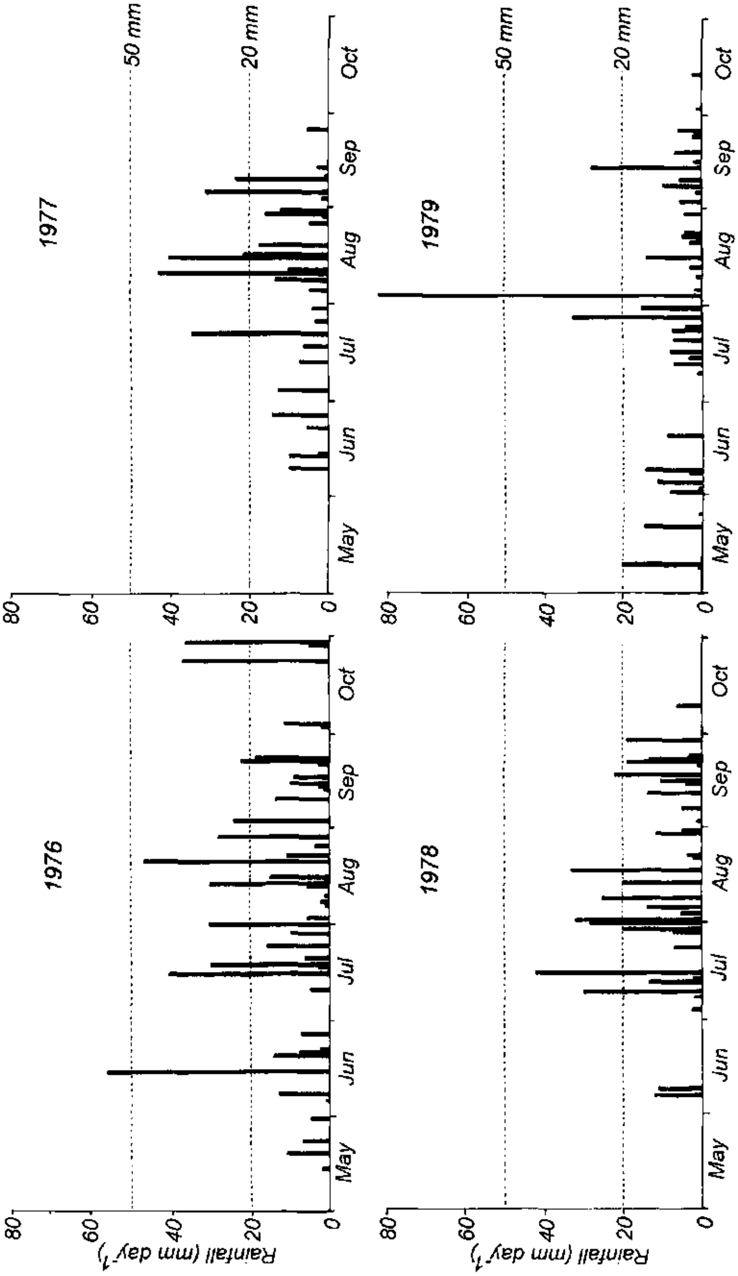


Fig. 14. *Daily rainfall at Niono in the cropping seasons of 1976-1979.*

The number of >20 mm storms per season was quite small, no more than 25% of the total number. However, their contribution to the total amount of rain was more than 50% (Table 6). Rainfall intensity has been described by Hoogmoed (1981b) and results are summarized in Fig. 15. It is clear that rainfall may show very high intensities: in 1979 a peak of 300 mm h^{-1} was recorded! However, duration of these peaks is usually no more than 5 min.

Table 6. *Distribution of rainfall events over three size classes, Niono, 1976-1979.*

Year	Total (mm)	<10 mm		10-20 mm		>20 mm	
		(mm)	(rel)[a]	(mm)	(rel)[a]	(mm)	(rel)[a]
1976	578	100	17	113	20	365	63
1977	370	57	15	124	34	189	51
1978	412	97	24	138	34	177	43
1979	402	111	28	74	18	217	57

[a] Total amount per year = 100%

The curves clearly show the differences between small and large storms. No correlation however was found between storm size and intensity. For comparison, data from Niamey (Niger) and Hyderabad (a comparable semi-arid region in India) were also analyzed. Rainfall charts from Niamey were supplied by the Meteorological Service of Niger, from Hyderabad by ICRISAT (The International Crops Research Institute for the Semi-Arid Tropics). The reason for choosing the latter data was that at ICRISAT soil management systems for the semi-arid tropical regions are also being studied (ICRISAT, 1981a).The rainfall in Niamey was comparable to the Niono (Mali) rainfall, but rainfall intensity in India was lower than in West Africa (Fig. 15). Values for different expressions of the erosive power of the rain (E; E>25; AI_m) are given in Table 7. The values for Niono (Mali) are about the same as for Niamey (Niger). The higher values per mm of rain for Niono compared with Hyderabad (India) again confirm the higher aggressiveness of the rain in West Africa. This is mainly caused by the higher intensity in Niono; comparing E mm^{-1} gives values of 26 and 24, comparing E>25 mm^{-1} gives values of 16 and 10 respectively for Niono and Hyderabad.

Infiltration

Fig. 16 (left) shows three curves for the infiltration rate of an undisturbed (naturally crusted) soil as a function of time. One curve represents infiltration in the dry soil and two curves represent re-infiltration of the same sample area at 1 and 14 days after the first wetting, respectively. The infiltration curve for 1 day is below the curve for the dry soil because the still very wet soil has a lower absorption capacity. Also, the final infiltration rate is somewhat lower due to the formation of a slightly more impermeable crust during subsequent artificial rains.

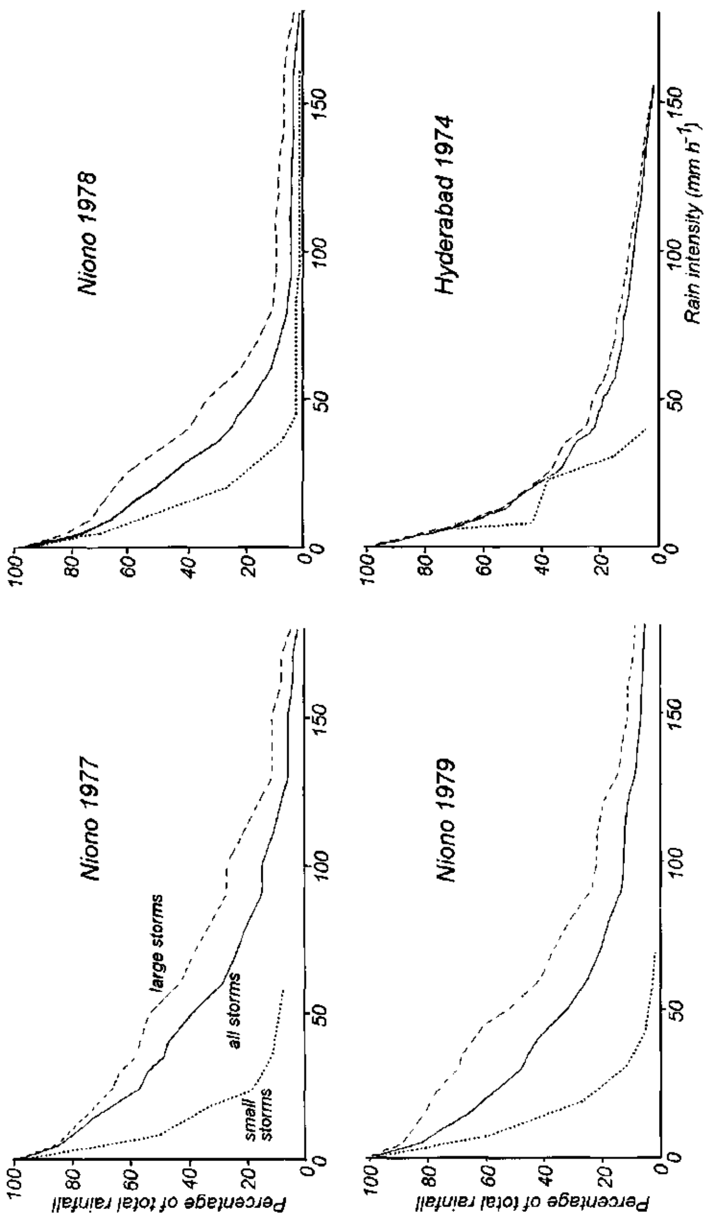


Fig. 15. *Percentage of rain below a certain intensity (mm h^{-1}) for Niono (1977, 1978 and 1979) and for Hyderabad, India (1974). Large storms >20 mm; small storms <10 mm.*

Table 7. *Kinetic energy and erosivity of rain over a complete rainy season for Niono (Mali), Niamey (Niger) and Hyderabad (India).*

	Niono (Mali)				Niamey (Niger)	Hyderabad (India)
	1977	1978	1979	Mean	1970-1972	1974-1977
Total rain (mm)	376	331	397	368	392	628
Total kinetic energy E (10^3 J m^{-2})[a]	10.1	8.2	10.5	9.6	10.6	15.0
Total kinetic energy E >25 (10^3 J m^{-2})[b]	6.6	4.5	6.6	5.9	6.8	6.2
Total erosivity index AI_m (10^3 mm h^{-1})[c]	18.0	10.2	18.5	15.6	20.7	16.4
E mm^{-1}	27	25	27	26	27	24
E > 25 mm^{-1}	18	14	17	16	17	10
AI_m mm^{-1}	48	31	47	42	53	26

[a] Wischmeier and Smith (1978). [b] Hudson (1971). [c] Lal (1976).

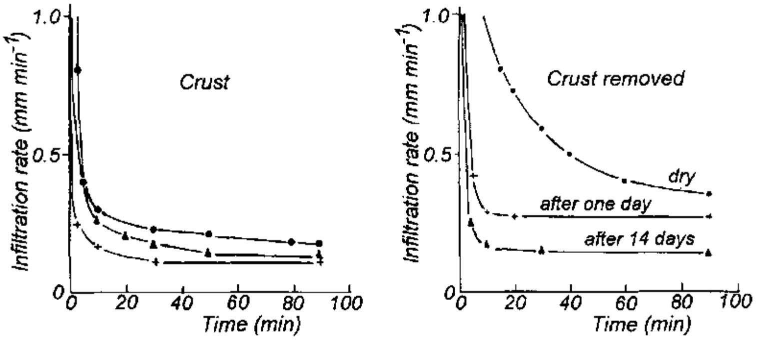


Fig. 16. *Infiltration rate as a function of the time of wetting for a permanent crusted soil and for soil where the crust was carefully removed just before the first wetting.*

Fig. 16 (right) shows the infiltration rate of a soil where the original crust was carefully removed. The curve for dry soil shows (compared to the corresponding curve in Fig. 16 (left)) a dramatic increase in infiltration rate due to the absence of a crust. One day after the first wetting, the infiltration curve was already far below the dry curve. Again, this is partly due to the very wet state of the soil which decreases the absorption capacity of the soil for water. However, this is also due to the formation of a new crust during wetting. This is indicated by the infiltration curve 14 days after the first infiltration. It might be expected that this curve, due to drying of the soil should be situated in between the other two, as

was the case for the crusted soil. However, the 14 days curve is the lowest of all three. This indicates that during the wetting/drying cycles the soil forms a new, less permeable surface crust. Obviously, this is a fast process; already during the third shower after the original crust had been removed the infiltration rate dropped to the low values normal for crusted soils (cf. Fig. 16 (left)), indicating an almost complete restoration of such a crust.
Fig. 16 shows that the final infiltration rate was about 10 mm h^{-1}. This value should be of about the same order of magnitude as the saturated hydraulic conductivity of the crust. The saturated conductivity of uncrusted soil is of the order of 100-200 mm h^{-1} (Stroosnijder, 1977). Thus, it may be concluded that the thin crust is at least 10 times less permeable than the directly underlying soil.

Another proof of the presence of a crust is the soil moisture content immediately after wetting of the soil. It has been found (Hoogmoed and Kievit, 1981) that in the crusted soil the moisture content just below the crust was only 15-20% (w/w), while in a non-crusted soil this value was 30-35% (w/w). This difference is due to the large drop in pressure head over the depth of the crust; below the crust it has already reached a significant negative value. Thus, in the subsoil, where the soil moisture content will never exceed the observed values of 15-20% (w/w), the infiltration of water is in fact an unsaturated infiltration.

2.3.4. Discussion

Rainfall

Detailed data on rainfall in the West African Sahel are scarce; Cochemé and Franquin (1967) reported only 35 meteorological stations to serve an area of over 2 million km^2! Since not all stations are equipped with recording rain gauges, information on the intensity of rainfall is even more scarce. In Senegal, Charreau and Nicou (1971) found for the rainfall in Bambey (550 mm $year^{-1}$) that 3/4 of the total rainfall had an intensity of >8.6 mm h^{-1}, 1/2 of >26.7 mm h^{-1} and 1/4 of >52.4 mm h^{-1}. Kowal (1970) states that for rainfall in northern Nigeria, over the past 45 years, peak intensities of over 250 mm h^{-1} were not uncommon for very short periods of time.
In the present study, it has been shown that rainfall distribution over the growing season in the southern part of the Sahel is such that millet cropping should be possible. However, given the minimum length of the growing cycle of millet in order to obtain a reasonable grain harvest, it is important that crop growth starts as early as possible. Sowing can often be performed only in wet soil since dry soil is too hard to till. Moreover, rainfall may be so erratic that there is a considerable risk that the amount of water stored in the soil may not be enough to keep the young plants alive in the early season and fields have to be resown. When runoff losses could be decreased or avoided, the risk of exhausting the water stock in the soil by the young crop would also decrease.

Runoff losses could be adequately decreased or avoided by tillage practices especially designed for and adjusted to the larger rainstorms since the contribution to runoff by the largest storms is very large. For example, in 1979 the largest single rain event was > 80 mm (= 25% of total annual rainfall) and runoff was about 80%, which is almost 44% of total annual runoff. Large runoff losses were also reported by Delwaulle (1973) for similar conditions in Niger. These runoff losses may be explained by the high intensity of the rainfall during these large storms, causing, firstly, the infiltration capacity to be quickly exceeded and, secondly, on a tilled surface, an aggravation of the crust formation process. In view of the high intensifies of West African rain, the design criteria for new soil management techniques applicable in other semi-arid areas do not apply for the Sahel. The positive effect of tillage on water storage on these sandy soils disappears much quicker, while on the other hand the storage requirements are higher.

Crust properties

For natural untilled soils the effect of successive wettings on crust formation is small and one may assume that for these soils (used for extensive grazing in the Sahel) crust properties are constant and do not vary significantly over the year. However, where tillage is practiced, one must clearly be aware of the danger of crust formation, although the crust influences only water movement and not seedling emergence. A mathematical description of the infiltration process on permanently crusted soils and on tilled soils will be given in case 6.

2.3.5. Conclusions

(1) Crusts on the sandy soils used for millet cropping in Mali are very thin but they seriously limit water infiltration.
(2) The main cause of crust formation on sandy soils is the high intensity of the rain, which has a high impact (kinetic energy) on the soil surface.
(3) On freshly tilled soil a new crust is quickly formed after only a few rainstorms. This reduces the duration of the positive effect of tillage on water infiltration to a few weeks.
(4) With present-day runoff from farmers' fields, so much water is lost that in an average year the available soil water is just sufficient for a marginal grain harvest. However, in a dry year a serious crop failure may be expected.
(5) Research should be concentrated on soil management practices which avoid runoff and thus dramatically decrease the risk of crop failure in millet growing in the south of the Sahel.

2.4. Case 2. Soil management for crop production in the West African Sahel. I. Soil and climate parameters

2.4.1. Introduction

The world's attention continues to be drawn to food shortages in the Sahel region of West Africa. Although drought periods generally are the direct cause of disasters, agricultural research has shown that the problems of insufficient food crop production are not just due to these adverse climatic conditions, but to a combination of environmental and socioeconomic factors (Matlon, 1987). Here, and in case 4, research on soil and-water-management of typical West African soil types, carried out at ICRISAT's Sahelian Center near Niamey, Republic of Niger, will be described.
In this case study, investigations are reported concerning the two most important environmental parameters that affect soil management, i.e. soil and rainfall.

2.4.2. General description of the area

In West Africa, the vegetation zones closely follow the isohyets of annual rainfall, which run virtually east-west and show a substantial increase in annual precipitation when moving south, away from the Sahara desert. The Sahelian and Sahelo-Sudanian zones are bordered by average annual rainfall limits of 100 mm year^{-1} in the north (approximately the northern limit of cultivation) and 600 mm year^{-1} in the south, from where the Sudanian and Sudano-Guinean zones extend to the south to the maximum rainfall limit of about 1200 mm year^{-1}. The single-peak rainy season is in the period from May to September, with the remainder of the year virtually dry. The length of the rainy season ranges from 60 days at the 250 mm year^{-1} isohyet to 120 days at the 750 mm year^{-1} isohyet. Rainfall is irregular and comes in the form of high-intensity storms, with strong implications for soil management and soil and water conservation.
Generally, productive arable farming is not possible in regions with < 400 mm year^{-1} rainfall. In these regions, agricultural production is based on cattle (meat and milk products), often in a nomadic herd system. Pearl millet (*Pennisetum glaucum* (L.) R.Br.) is grown throughout the semi-arid zone, but it is dominant in the 250-750 mm year^{-1} zone. Millet is often intercropped with cowpea or niebe (*Vigna unguiculata).* The production of sorghum (*Sorghum bicolor* (L.) Moench) is concentrated in areas with 650-1000 mm year^{-1} rainfall.
Crop production in the Sahelian region is hindered by a large number of unfavourable factors. The soils have a low fertility and an unstable structure, the climate is harsh and unpredictable, and the means of the farmer in terms of capital, energy and economic infrastructure are extremely limited. Traditional crop production is almost entirely based on hand labour. Animal traction is used to some extent (mainly in Senegal and Mali) in the production of the typical subsistence crops millet, cowpea and sorghum. Mechanization by using tractors

is limited to a few large-scale operations producing cash crops.
For a typical Sahelian farm soil management forms a very important part of the energy input. Seedbed preparation may constitute the biggest energy consuming activity, but manual weeding may form the most serious labour bottleneck of all activities.

2.4.3. The experimental site

The ICRISAT Sahelian Center (ISC) is situated in the south-western part of Niger, at 13°15' N latitude and 2°18' E longitude, about 40 km south-east of the capital Niamey, and about 7 km from the Niger river (cf. Fig. 4).
The soils in the Niamey region, having moist conditions for 98 consecutive days, are classified as Ustic. Mean annual soil temperature is 31.5° C, and the temperature regime was classified as Isohyperthermic (van Wambeke, 1982). The hottest period, however, is in April-May and not in the summer months. Thus, because of larger differences between extremes, Hyperthermic would be the best classification (Soil Survey Staff, 1975). The most important soil series at the center, the Labucheri, is classified as a Psammentic Paleustalf (West et al., 1984).
The experimental site has a rather flat topography: slopes are generally around 1-2%, with a maximum of 4%. The soil profile is deep, ranging from a minimum of 2 m up to more than 8 m at the bottom of a slope. The main characteristics of the soil are given in Table 8. On a micro-scale, with locations no more than 10-20 m apart, variations in crop growth and yield are appreciable. The reason for this extreme variability is not well understood, but is thought to be caused by both chemical and physical differences. Research on the chemical aspects of this variability has been reported by Scott-Wendt et al. (1988).

The typical conditions of soil and climate make it difficult to grow crops successfully. Millet is planted immediately after the first substantial rain, but the young seedlings frequently are killed, either by lack of water because of a dry spell after the first rain, or by sand blasting or burying by sand as a result of strong winds accompanying the rains early in the season.

Soil physical characteristics

In the Niamey region, the texture of the soil is very light without any natural aggregation. Thus, the soil shows a typical behaviour: when it is dry, manipulation in the field (by traffic, tillage, etc.) may result in a very loose top layer which easily blows away. However, when the soil is moist, its appearance and behaviour are completely. different: the soil surface is resistant to wind, and relatively stable aggregates can be formed by tillage. This leads to a limited number of moisture-dictated conditions, where the surface soil may be successfully modified by tillage operations.

Table 8. *Soil characteristics at ISC.*

Characteristic	Depth (cm)		
	0-5	5-10	20-25
pH (KCl)	5.2	4.7	4.5
Organic matter (%, w/w)	0.5	0.6	0.5
Texture (%, w/w)			
0 - 2 µm	3.1	3.1	6.2
2 - 16 µm	1.3	1.6	1.1
16 - 50 µm	3.3	3.2	2.7
50 - 105 µm	19.8	19.7	18.3
105 - 150 µm	14.4	13.9	14.4
150 - 2000 µm	58.1	58.5	57.3
Particle density (g cm^{-3})	2.66	2.66	2.66
P_2O_5 (mg l^{-1})	6.5	5	5.5
K_2O (mg 100 g^{-1})	2.5	2	2
pF values (%, w/w)			
2.0	6.1	6.1	6.2
2.3	3.1	3.3	3.8
2.7	2.2	2.4	3.0
3.4	1.4	1.5	2.3
4.2	1.1	1.2	1.8

To supply a basis for further investigations, the following soil characteristics were determined: (1) particle size distribution, organic matter, P and K contents; (2) moisture retention curve, saturated and unsaturated conductivity; (3) mechanical behaviour of the soil, in response to tillage activities and traffic. The effects of the tillage-induced structure modification on soil strength, bulk density and wind erosion susceptibility, were assessed.

Rainfall

Two aspects were investigated in more detail, as these have the highest impact on the actual choice of tillage and planting activities: (1) the aggressiveness of the rainfall, as affecting the physical condition of the soil, in particular the surface layer; (2) the rainfall distribution.

The kinetic energy of the falling drops, which is primarily responsible for erosion and runoff phenomena in the field, is strongly related to the intensity of the rain. Rainfall intensity also influences the water balance: the infiltration capacity may be decreased by seal formation, and surface storage may be reduced by a smoothening of the soil surface.

In the Niamey region, the rainfall distribution has some characteristics which are particularly important for soil management. (1) Rainfall early in the season is very erratic. Single showers may wet the soil sufficiently for planting, but may be followed by a long dry period (Sivakumar et al., 1979). (2) Highest crop yields were found when the crop was planted just after the first showers. One of the

possible causes is the so-called 'N-flush', i.e. a process of nitrification in the soil by microbial activity, initiated when the soil is wetted after a long dry period (Birch, 1960). (3) Rainy days may be immediately followed by days with high evaporative demand. In view of the very low moisture-holding capacity of sandy Sahelian soils, crop management decisions following a rainfall event should be made very quickly.
By analysing daily rainfall data, the number of workable and plantable days was calculated, based on assumptions derived from observations in the field.

2.4.4. Materials and methods

Basic soil data

Particle size distribution: Particle sizes <0.05 mm were determined by the pipette method, the larger sizes by sieving (Gee and Bauder, 1986).

pH, organic matter, P and K: The pH was determined using the KCl method (McLean, 1982); organic matter content (total C content) was determined by the dry combustion method (Nelson and Sommers, 1982). In addition, K (soluble in oxalic/hydrochloric acid) and P (soluble in water) contents of the soil were determined.

Particle density: This characteristic was determined by the pycnometer test (Blake and Hartge, 1986).

Data relating to water balance and water movement

Moisture retention curves: The following methods were used (Richards, 1965): sand beds (suction range 1-10 kPa), sand-kaolin beds (20-50 kPa) and pressure-plate equipment (100-1500 kPa). Curves were determined for two dry bulk densities (1.40 and 1.60 g cm^{-3}), which were obtained by compaction of dry, structureless sand in sample rings. The rings were left to saturate for 48 h before applying the consecutive suctions.

Saturated hydraulic conductivity (K_{sat}): The constant-head method was applied (Klute and Dirksen, 1986), using core samples of about 10 cm high, with an internal diameter of 5 cm. The hydraulic head difference with the bottom of the sample was about 12 cm. Tests were carried out for a range of soil bulk density values.

Unsaturated hydraulic conductivity: For the determination of the unsaturated hydraulic conductivity (K) as a function of moisture content, the so-called 'hot air method' was used (Arya et al., 1975; Van Grinsven et al., 1985). The structureless sandy soil allows cylinders to be filled quite accurately and uniformly. However, moisture contents higher than field capacity (about 10%, w/w) cause non-uniform distribution of water in the sample. Therefore only a small moisture range can be analysed, but this is the most interesting range in water balance calculations.

Data relating to the mechanical behaviour of the soil

Mechanical compaction: The response to mechanical compaction was assessed for: (1) samples of the original soil; (2) samples of the same soil with increased organic matter content. This increase was obtained by mixing old, well-decomposed farmyard manure (FYM) with 15 % dry matter with the soil at a rate of 75 t ha^{-1} (dry matter). The mixture of soil and FYM was left for 2.5 months and then the larger remaining parts such as straw were removed. Testing according to the potentiometric Kurmies method (Houba et al., 1979) showed that organic matter content had increased from 0.12 to 0.38% (w/w).
All samples were wetted to two moisture content levels: 5 and 10% (w/w). The moist soil was placed in cylindrical PVC containers (diameter 11.6 cm, height 4 cm) with a fixed bottom. Then the soil was subjected to piston pressures of 15, 34 and 53 kPa, respectively, for about 30 s.
In a second series of tests, the indoor soil bin of the Tillage Laboratory was used. This model soil bin consists of eight 50-cm long, aluminium U-profiles with a height and width of 0.2 m, laid together to form an uninterrupted length of 4 m. Soil was wetted to moisture contents of 4, 6 or 8% (w/w) and then placed in the soil bin. A standardized precompaction procedure resulted in a homogeneous dry bulk density of 1.35 g cm^{-3}.
Compaction of the top soil was achieved with a smooth steel roller (diameter 20 cm, width 19 cm) which can be moved with adjustable forward speed. Both the pressure exerted on the soil by the roller and the rotational speed of the roller can be adjusted. A forward speed of 0.2 m s^{-1} and rotational speeds of 20, 30 and 45 r min^{-1}, respectively, resulted in 0, 30 and 55% positive slip. Effective load of the roller was 2.5 or 6.5 kg. Since the depth of the rut formed by the roller could not be measured exactly, the resulting pressures (2 and 4 kPa) could only be approximated.

Measurements

Tensile strength: The tensile strength was assessed by means of the 'Brazilian test' (Dexter and Kroesbergen, 1985). After soil compaction, small brass sample rings (diameter 35.6 mm, height 13 mm), with a cutting edge on one end, were pressed into the moist surface of the soil in the bin, which was then placed under heating light bulbs to attain soil surface temperatures of about 50° C, simulating drying under strong sunlight. The samples were left under the lamps until the top layer was air dry. The brass rings were then lifted out of the surface layer and cylinders of dried soil were carefully pushed out of these rings. The soil cylinders were (placed on their side) subjected to loading until failure occurred.

Bulk density: Bulk density was measured using parts of the broken soil cylinders after the measurement of tensile strength. The density of these clods was determined by immersion in kerosene (McIntyre and Stirk, 1954).

Cone index (CI): The CI, defined as measured penetration resistance (N) / cone base area (m^2), is a mechanical characteristic which depends on soil moisture content, bulk density and strength of the bonds between the mineral parts. In clay soils, cohesion is the most important parameter; in sandy soils, the internal friction. Penetration speed in the tests was 10 mm min^{-1}. The cone used had a top angle of 600 and a base area of 0.2 cm^2. The CI was taken as the peak value recorded for the first 5 mm of penetration.

Wind erosion susceptibility of the treated soil surface: For these experiments, a simple wind tunnel (2.5 m long, cross section 0.2 x 0.2 m) in the Tillage Laboratory was used. The model soil bin was placed under an opening in the bottom of the tunnel, to ensure that the surface of the soil was in line with this bottom. Since the process of abrasion by soil particles present in the air stream is primarily responsible for soil detachment and transport, 400-500 g min^{-1} of soil material (<1 mm) was brought in the air stream before it passed the soil surface. During the standard 2-min duration of the test a wind speed of 7.5 m s^{-1} was maintained.

Rainfall

Information on rainfall characteristics was collected and analysed for five locations in the typical millet-growing regions of Niger, and for one comparable location in India. Details of the locations are given in Table 9.

Table 9. *Details of the data available for rainfall analysis.*

Location	Lat. (N)		Long. (E)		Intensity analysis				Workable days		
	o	'	o	'	Period	Nr. of yrs	Nr. of st.	Total rain (mm)	Period	Nr. of yrs	Mn. ann. rainfall (mm)
Tahoua	14	54	05	15					1921-1984	64	384
Zinder	13	48	09	00	1969-1983	15	335	5474	1905-1984	76	473
Niamey Ville	13	29	02	10	1971-1983[1]	12	343	6171	1905-1984	79	559
Niamey Aer.	13	29	02	10	1970-1983[1]	13	370	5963			
Maradi	13	28	07	05	1970-1983[2]	13	305	4626	1931-1984	50	573
Gaya	11	59	03	30	1970-1983[3]	12	537	9289	1931-1984	54	825
Patancheru, India	17	27	78	28	1974-1983	10	377	7377			

[1] 1979 missing. [2] 1980 missing. [3] 1971 and 1972 missing

Intensities: To determine the intensity of each rainfall event, charts from recording rain gauges were used. Events were separated by rainless periods of at least 12 h. Kinetic energy and various indices, based on their empirical relationship with rainfall intensity were calculated in the same way as described in case 1. Compared to case 1, a much larger dataset from Hyderabad and Niamey was analysed, allowing a statistically better analysis.

Workable periods

The assumptions (Table 10) used in the calculation of the number of workable days are based on field observations and measurements on sandy soils. Basically, it is assumed that soil can be tilled satisfactorily when the topsoil is sufficiently moist. However, moisture content will drop quickly under dry weather after rain. In the analysis, the length of the workable period depends on the volume of rainfall falling in 1 day or in 2 consecutive days. Although many variations are possible, two different lengths of workable periods were evaluated, and only one length of plantable period, since the decision to plant is more critical than the decision to till. Table 10 shows that Scenario 2 is somewhat more optimistic about the number of workable days after a certain amount of rain has fallen than Scenario 1.

The analysis was carried out over the soil preparation and planting period that is typical of the location. The period began on 1 May for all locations and ended on 28 June for Tahoua and on 18 July for the other locations. Planting after this period was assumed to leave too short a growth period to expect any harvest. Planting and tillage activities were assumed to take place the day (s) after the first day with sufficient rainfall, even when it rained again on that particular day.

Table 10. *Rainfall threshold values (rainfall in mm, falling in 1 or 2 consecutive days) and assumed number of workable and plantable days after the rainfall event.*

Rain	Assumed number of workable days		Rain (mm)	Assumed number of plantable days
	'1'	'2'		
Rain < 6	0	0	Rain < 11	0
6 ≤ rain <14	2	3	11 ≤ rain < 19	1
14 ≤ rain < 21	3	4	19 ≤ rain < 26	2
Rain ≥ 21	4	5	Rain ≥ 26	3

[1] In 1 day; for 2 days, threshold values plus 2 mm
[2] '1' = Scenario 1; '2' = Scenario 2
[3] In 1 day; for 2 days, threshold values plus 5 mm

2.4.5. Results and discussion

Soil

The basic soil physical characteristics were given in Table 8. In the upper 10 cm layer, clay and silt contents total no more than 5-7% (w/w). The dominant clay mineral is kaolinite (West et al., 1984). The coarse sand fraction occupies almost 60% (w/w) of the total. Organic matter content is very low (0.4-0.6%, w/w).
The moisture retention curves for two bulk densities, the saturated hydraulic conductivity (K_{sat}) as a function of bulk density and the relationship between unsaturated hydraulic conductivity (K) and moisture content, are shown in Figs. 17, 18 and 19, respectively. The results indicate that the soil at ISC is a typical coarse sandy soil, with a very small water-holding capacity. Therefore, in the field soon after rainfall soil moisture values quickly drop to levels under 10% (w/w), as the water drains quickly from the large pores.

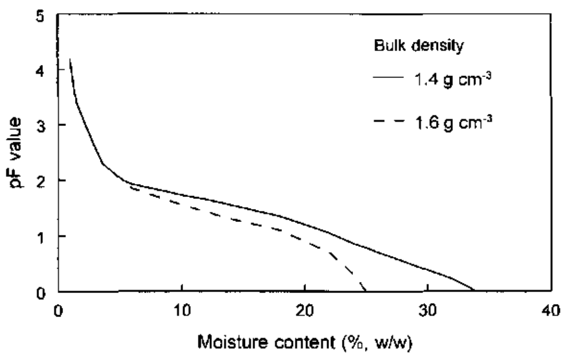


Fig. 17. *Moisture retention curve for two bulk densities (ISC soil).*

Changes in soil bulk density under load are shown in Fig. 20. A higher organic matter content clearly reduces the increase in bulk density after loading, indicating that the soil becomes less susceptible to compaction. In all cases a higher moisture content at compaction results in a higher bulk density.
Fig. 21 shows the tensile strength of the soil, as manipulated by various methods. The effect of a roller with positive slip (imitating a sliding movement of a metal tool over the soil) is compared with a static load, applied at different moisture levels, for an otherwise untreated soil. A higher moisture content at the time of manipulation leads to higher tensile strength. The effect of positive slip is very large, since a load of only 4 kPa but with 30% slip causes the same tensile strength of the soil top layer, as does a load of 53 kPa without slip at an even higher moisture content. Most probably this effect can be explained by the fact that slip causes a more intimate contact between the soil particles (rearrangement).

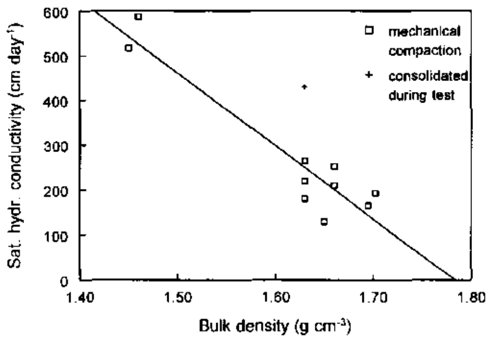


Fig. 18. *Effect of bulk density on saturated hydraulic conductivity (ISC soil).*

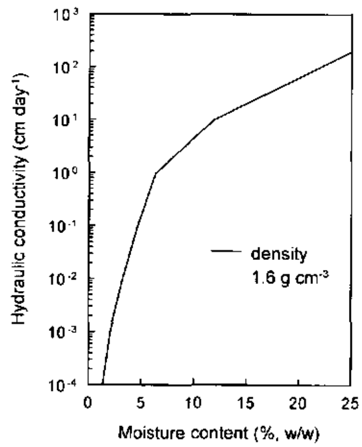


Fig. 19. *Hydraulic conductivity as a function of soil moisture content (ISC soil).*

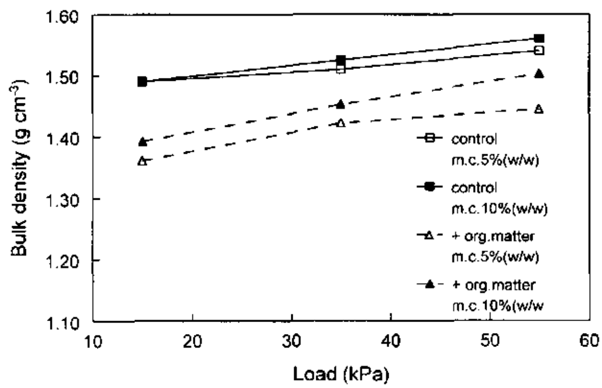


Fig. 20. *Influence of moisture content and increased organic matter content on the effect of static loading (ISC soil).*

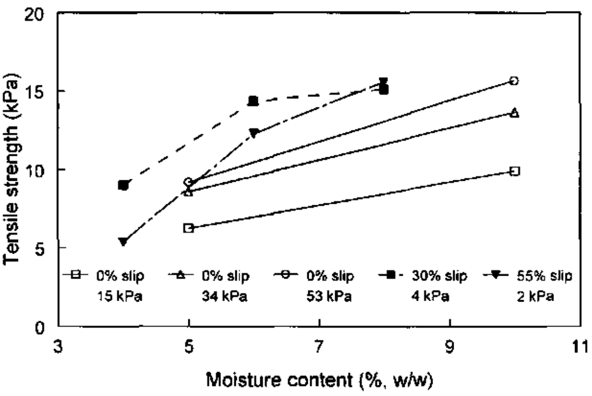


Fig. 21. *Effect of load, slip and moisture content on tensile strength of the top layer (ISC soil).*

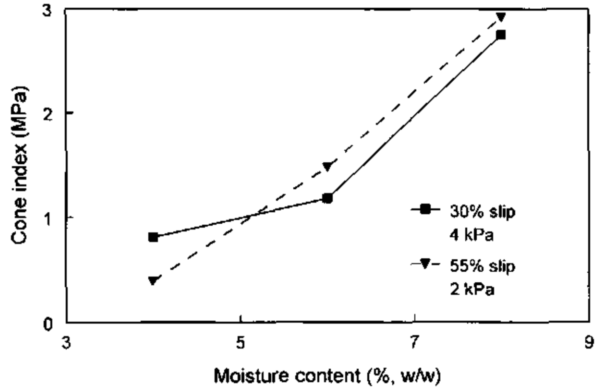


Fig. 22. *Effect of load, slip and moisture content on penetration resistance (cone index; (ISC soil).*

The load- and slip-induced increases in tensile strength and bulk density cause higher resistance to penetration (Fig. 22). Soil detachment from the samples subjected to wind loaded with sand was reduced considerably when the surface was smeared and compacted with the driven roller (Fig. 23).
These results of the smearing and compaction experiments show that the best quality of work can be achieved by tillage operations in wet soil. Clods or ridges made in a soil with a moisture content near field capacity will remain more stable. The effects of sliding of a tool over the soil surface also show that a stable and strong surface layer does not require a strong compaction of the soil, i.e. simple implements (bed shaper, ridger with wing attachment) may be considered to protect the soil surface to wind erosion, by sealing it.

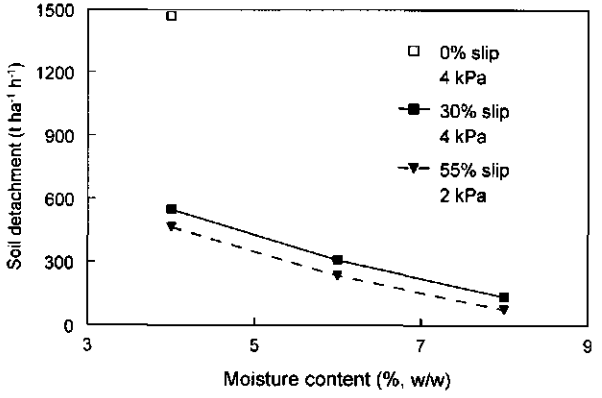


Fig. 23. *Effect of load, slip treatments on wind erosion susceptibility, expressed as soil detachment (ISC soil).*

Rainfall intensities

Here, the most important results of the analysis will be given; a detailed discussion of the data may be found in Hoogmoed (1986). Fig. 24 shows that 50% of the rain in Niger falls with intensities >30 mm h^{-1}, against 15 mm h^{-1} in India. This means that although the region of study in Niger and the area around Patancheru (Andhra Pradesh) in India both have a semi-arid tropical climate with about the same total rainfall, there is considerable difference in rainfall intensity. In the analysis, rainstorms were divided into three classes: <10 mm, 10-20 mm and >20 mm. For Niamey, Niger, the clear differences in intensity distribution between small and large storms are shown in Fig. 25.

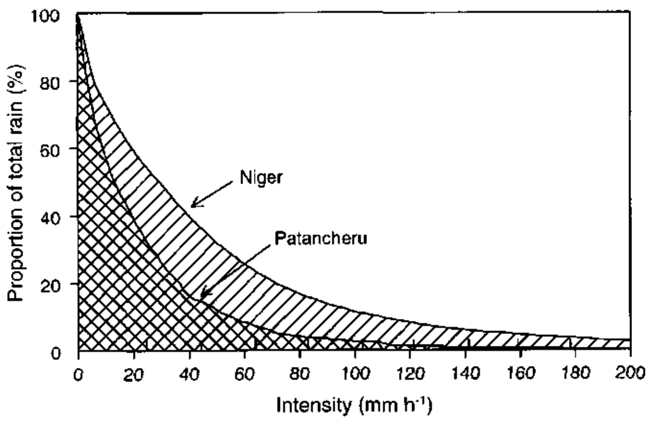


Fig. 24. *Difference in intensity distribution between the Niger locations and Pantancheru, India. Average values for all storms analysed.*

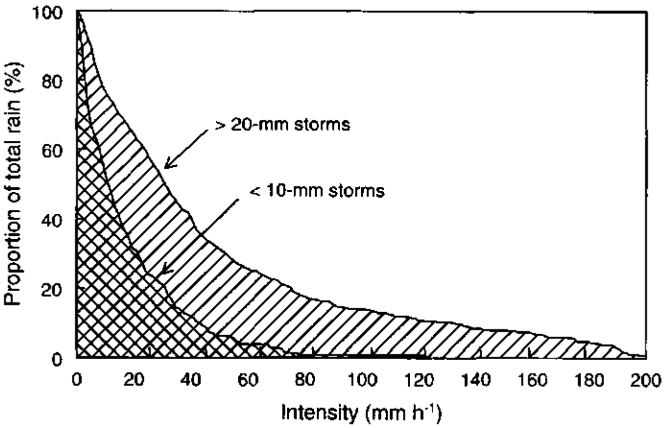


Fig. 25. *Intensity distribution of small (<10 mm) and large (>20 mm) storms for Niamey (Ville), Niger.*

Table 11. *Energy and erosivity indices expressed per mm rainfall for five locations in Niger and one location in India.*

Location	All storms				Storms < 10 mm				Storms > 20 mm			
	E_k	EI_{30}	E_k>25	AI_m	E_k	EI_{30}	E_k>25	AI_m	E_k	EI_{30}	E_k>25	AI_m
Niamey Ville	23	1050	15	51	20	254	6	19	25	1378	18	64
Niamey Aero	23	888	14	45	20	285	7	18	24	1145	16	55
Zinder	24	1059	17	58	21	350	8	22	25	1376	19	74
Maradi	23	833	14	42	21	267	7	19	24	1098	16	50
Gaya	23	824	13	40	20	231	5	15	23	1045	15	48
Patancheru India	21	667	8	23	18	152	3	10	22	829	10	26

Units: E_k = J m^{-2} mm^{-1}; EI_{30} = J m^{-2} h^{-1}; E_k >25 = J m^{-2} mm^{-1}; AI_m = mm h^{-1}.

The various indices, based on the intensity (distribution) of the rainstorms, are summarized in Table 11. These values are expressed per mm rainfall, and may thus be considered as an indication of rainfall aggressiveness. For all storms, Table 11 indicates a small difference between locations in Niger, the lower rainfall areas having higher index values, and confirms the (aforementioned) big difference between Niger and Patancheru, India. The indices, expressed per mm rain, are clearly higher for the storms >20 mm. However, although the storms >20 mm have a larger proportion of high-intensity rain than the storms <10 mm, regression analysis showed a very poor relationship between storm size and energy per mm rainfall. The other indices also showed poor fits (Table 12).

Table 12. *Goodness of fit (r^2 values) regression analysis of indices versus storm size for locations shown in Table 11.*

Type of fit	Index				Index per mm rainfall			
	E_k	EI_{30}	E_k>25	AI_m	E_k	EI_{30}	E_k>25	AI_m
Linear	0.98	0.75	0.79	0.60	0.21	0.52	0.23	0.28
Power	0.98	0.85	0.75	0.79	0.29	0.55	0.01	0.39

This means that a large variation exits between individual storms. On the other hand, the kinetic energy (E_k) showed a good linear correlation with rainstorm size, which is not surprising in view of the origin of the calculation. So, larger storms are not always more aggressive than smaller ones, but they will have a larger influence on the water balance, since total erosivity is higher. For most of the indices, a linear fit was best. The following equation was found for Niamey:
$E_k = -40.5 + 25.67 \times \text{rain (mm)}$ ($r^2 = 0.988$)
and for Patancheru
$E_k = -24.2 + 22.14 \times \text{rain (mm)}$ ($r^2 = 0.982$)

As part of the analysis, possible runoff was calculated for each storm, assuming various combinations of infiltration capacity and surface storage capacity.

These soil characteristics were assumed to remain constant during the storm, which is of course not quite true, but results give an indication of what may happen under different rainfall regimes. Fig. 26 shows that large storms will cause higher runoff losses, or require higher surface storage values to keep these losses low.

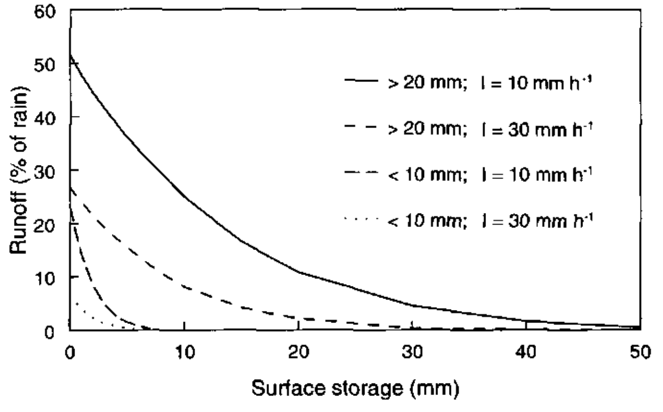


Fig. 26. *Calculated effect of surface storage on runoff values under small and large storms (<10 mm and >20 mm), for two infiltration rates (10 and 30 mm h^{-1}) for Niamey (Ville), Niger.*

Further analysis of the rainfall data showed that the variability of the rainfall is highest in the locations with the lowest rainfall (Table 13).

Table 13. *Characteristics of the rainfall in the periods analysed.*

Location	n	Mean (mm)	S_x (mm)	Min. (mm)	Max. (mm)	Skew-ness	SE (skew)	80% confidence[1]	
								Min. (mm)	Max. (mm)
Tahoua	63	68	40	5	171	0.80	0.30	16	120
Zinder	74	143	67	25	318	0.45	0.28	57	229
Niamey Ville	79	192	68	32	402	0.11	0.27	105	279
Maradi	49	174	68	57	314	0.33	0.34	87	261
Gaya	53	298	87	131	518	0.27	0.33	187	409

[1] Assuming normal distribution

This analysis, however, does not account for the size or distribution of the individual storms. This information was used to calculate the average number of work days (for two scenarios) and planting days per location (Table 14).

Table 14. *Calculated number of workable and plantable days based on rainfall analysis.*

Location	n (years)	Work days [1]			Plant days		Probability (%) of zero days to	
		'1'	'2'	S_x (%)	All	S_x (%)	Work	Plant
Tahoua	64	8.6	11.1	60	3.2	90	8	19
Zinder	76	16.4	20.0	44	7.6	58	1	5
Niamey	79	22.6	27.1	31	10.7	41	1	1
Maradi	50	19.6	23.6	38	9.3	50	2	2
Gaya	54	32.3	37.5	22	17.4	33	0	0

"1' = Scenario 1; '2'= Scenario 2 (cf. Table 10).

The driest location (Tahoua) shows very small numbers of available days, with an average of only 8.6 workable days for the most pessimistic scenario ('1'), and a 19% probability of not having any planting day.

These values are more favourable for the wetter locations, although the average number of plantable days in the 500-600 mm zone (Niamey, Maradi) does not exceed 11. In addition to the planting days, the farmer may have 5-15 days available for preparatory tillage.

Farmers' practice

The above mentioned conditions justify efforts to try to plant as early as possible, since at failure losses are small compared to the probable increase in yield. At this time of the year manpower is not required for other purposes and the loss of seed for planting is small (a few kg ha^{-1}). As will be shown in case 4, crop yields are greatly improved by appropriate management systems, including tillage, fertilizer application and the use of improved varieties.

2.4.6. Conclusions

From the laboratory experiments and rainfall analyses, the following conclusions may be drawn.

(1) The soil at ICRISAT Sahelian Center (ISC) is a structureless sand, with a high percentage of coarse sand particles, and a low organic-matter content.
(2) Mechanical treatment of the soil is effective only when the soil is moist. An external load compacts the soil, but only when the moisture content is sufficiently high.
(3) The soil surface can be made stronger, i.e. more resistant to wind erosion, particularly by smearing. In the early part of the season, this may be a practical option to protect the field against aggressive rain preceded by strong winds.
(4) In Niger, rainfall is very aggressive because intensities are high. This implies high energy impacts on the soil surface.
(5) Generally, the intensities of large storms are higher, but between the size of the storm and its intensity (or erosivity index derived from this intensity) no significant correlation was found when intensity was expressed per unit rainfall.
(6) For the sandy soil conditions as found at ISC, the number of days suitable for planting millet is on the average no more than 11. This situation demands a very efficient planting method and does not allow much room for elaborate, time-consuming seedbed preparation activities.

3. TILLAGE FOR SOIL AND WATER CONSERVATION

3.1. Tillage systems for SCH soils

Requirements set by agronomic and SWC needs will be translated by the farmer into a set of technical objectives to establish the desired soil structure or surface configuration of his field. He will try to reach these objectives by choosing equipment and operating this in the best possible way at the right moment. Individual operations form part of tillage or cultivation[11] systems. Although the objectives are of a technical nature, the implementation of these systems is governed by economic factors.

In the first place, the possibilities for preventing or curing problems with hardsetting are given in Table 15. Secondly, an overview of typical problems and management options for sealing and crusting soils is given in Table 16.

As an introduction to the discussion of the various systems, Table 17 presents an overview of tillage equipment, (commonly used implements, as well as those for special purposes) with an indication of the feasibility of application under different (socio-)economic conditions. A brief guide to the effectiveness of certain actions is also given.

Table 15*. Management by tillage of hardsetting soils.*

problem caused by hardsetting	preventive management	curative management
hard, massive, compact arable layer	- mulching - increase SOM - no-tillage, traffic lanes or broad beds to prevent additional mechanical compaction	a. use heavy machinery for primary tillage and subsequently apply intensive secondary tillage operations b. allow soil to soften by natural rain or irrigation and apply 'normal' tillage practices
hard, compact root zone	optimize water availability	deep tillage or subsoiling
low permeability of top soil	mulching	a. tillage to create macropores b. surface shaping to avoid losses of water by surface runoff

[11] Cultivation system is used here in the context of 'the activities needed to grow a crop', so not to be confused with cultivation in the meaning of 'working with a cultivator'.

Table 16. *Management by tillage of sealing and crusting soils.*

crust type	crust cause	crust problem	preventive management	curative management
for aggregated soils (clays and loams)				
structural crust	aggregate breakdown dispersion	emergence infiltration	creating a rough surface layer protection of soil surface by vegetation	mechanical crust breaking
depositional crust	sedimentation of disaggregated, dispersed soil particles in depressions	infiltration emergence	creating a rough surface layer	increase of surface detention mechanical crust breaking
for soils without structure (sandy / loamy soils)				
drying crust	repeated drying and wetting without direct raindrop impact	infiltration (slight)	creating a rough surface layer	mechanical crust breaking
layered structural crust	water drop impact, sorting of particles	infiltration sand drifting, wind erosion	protection of the soil surface	mechanical crust breaking
erosion crust	removal by wind or water of loose material from a layered structural crust	infiltration anchoring of wind-blown seeds	protection of the soil surface	mechanical crust breaking revegetation
runoff depositional crust	coarse material transported by runoff water and deposited on top of structural crusts	none*	prevention of runoff**	mechanical crust breaking
sedimentation crust	deposition of fine material in puddles with stagnant water	infiltration establishment of vegetation	controlled drainage (if preferred)***	mechanical crust breaking
pavement crust	outcropping of gravelly horizons after removal of crust and toplayer by erosion processes	infiltration establishment of vegetation	protection by vegetation	deep mechanical breaking of crusts and top layers revegetation

*: Not from the top layer, problem caused by the structural crust persists.
**: although this process often occurs in a field with ridges (deposition crust at bottom furrow).
***: it may be better when water can (slowly) infiltrate on the spot.

Table 17. *Tillage equipment and their possible use in cultivation systems.*

		cultivation system					effectiveness						
tillage phase	tool/implement	shifting cultivation	hand labour	animal traction	small tractors	highly mechanized	loosen (shallow)	loosen (deep)	break crusts	shape surface	crumble	pr. weed control	cur. weed control
p	handheld hoe	x	x				+	-	+	+	-	-	+
p	mouldboard plough			x	x	x	++	++	++	+	+	++	+
p	disc plough				x	x	++	+	++	+	+	+	+
p	chisel plough			x	x	x	+	++	+/-	-	+/-	+/-	-
p	Paraplow/Paratill					x	+/-	++	-	-	-	-	-
p	spade plough					x	+	+	-	-	+/-	+/-	+/-
s	spring tine cultivator					x	++	+/-	++	-	++	+	++
s	rigid tine harrow			x	x	x	+	-	++	-	+/-	+/-	+
s	disc harrow				x	x	-	-	+	-	+	-	+
s	roller harrow					x	-	-	++	-	+/-	-	++
s	rotating/reciproc. hoe					x	+	-	++	-	+	+/-	++
s	smooth roller			x	x	x	-	-	+	+/-	+/-	-	-
s	corrugated roller			x	x	x	-	-	++	-	+	-	-
s	'clod breaker'					x	-	-	+	+/-	++	-	-
sc	mouldboard ridger			x	x	x	+	+/-	+	++	+	+	+
sc	disc ridger				x	x	+/-	-	+	++	+/-	+	+
sc	bed shaper (bbf and W-form system)			x	x	x	-	-	+/-	++	-	-	-
c	tied ridger			x	x	x	-	-	-	+	-	-	-
c	sand fighter					x	-	-	+	+	-	-	-
w	rod weeder					x	-	-	+	-	-	-	++
w	handheld hoe	x	x	x			+	-	+	+/-	+/-	+	++
w	duckfeet / sweep weeder					x	+/-	-	++	-	+/-	+/-	++

p: primary tillage, s: secondary tillage, sc: surface configuration, c: conservation tillage, w: weeding
x: fits within cultivation system (cf. 3.2.1), combinations or chains of implements may form the tillage system (cf. 3.2.2)
++: highly suitable, +: well suitable, +/-: poorly suitable, -: not suitable, cur: curative, pr: preventive

Detailed information on the implements mentioned in Table 17 is found in Krause et al., 1984.

3.2. Relevant methods and techniques

The cultivation systems and the place of tillage in such systems, as presented in the previous tables will be discussed here. Firstly, a broad classification is given according to type and magnitude of energy and power use, and secondly a number of specific tillage systems (with emphasis on their SWC effect) is discussed.

3.2.1. Cultivation systems for crop production

Manual labour

Shifting cultivation. This is the most traditional system, where land is cleared from its original vegetation (trees, shrubs, grasses) and crops are grown for a short number of seasons, without external inputs like fertilisers, pesticides etc. Soil preparation, sowing and crop maintenance is done manually with simple hand-tools. The fields are abandoned when the yield level has decreased due to an exhaustion of the natural fertility or when weed infestation has reached unmanageable levels. Typical cycles are 2-3 years cropping and 10-15 years fallow (see e.g. Nye and Greenland, 1960).

Continuous cultivation with low external input. This system is based on the use of manual labour, but applying annual cropping, although fallow periods of 1 or 2 years may occur.
These systems may be found in two situations:

(a) subsistence based, this is generally the case when due to population pressure, the shifting cultivation system can no longer be applied. Risks for degradation are serious in this situation when too much protective vegetation (trees, shrubs etc.) is removed.
(b) cash or market crops production. Generally, inputs (particularly use of labour, but also application of manure or construction of simple SWC measures) are at a higher level than under (a).

Animal draught cultivation

Use of animals for traction can be found in (semi)continuous cultivation systems. The animals are used for tillage (main tillage, seedbed preparation), for weeding and for transport. Animal traction requires the purchase of simple equipment (ploughs, ridgers, harrows etc.).
This system requires a certain level of capital input: animals (even when the farmer owns cattle, the draught animals are taken out of milk and meat production) and the equipment. Investments for such a system can only be possible when there is cash income.

Motorization, use of fossil energy

Small tractor cultivation. In these systems, power sources with internal combustion engines are used, but with limited size and capacity. Typical examples are the two-wheel (walking) tractor and the small 4-wheel tractor with engines of less than 15-20 kW. Although the use of these small tractors may seem a logical step from animal traction towards a higher mechanization level, the use of small tractors (in particular the two-wheel tractors) is limited to garden-type cropping and high-input irrigated rice (with a strong concentration of its use in Asia). The low traction that can be exerted by these tractors (small wheels, low weight) and the difficulty and awkwardness to operate the tractor does not make these models very popular. For dryland farming, the small tractors are not able to provide enough draft force to allow tillage under dry soil conditions. In all, they seldom justify an economic investment (Holtkamp, 1990).

High input cultivation. In this system there is no limitation in the use of capital input for traction, fertilizers, seeds etc. Heavy machinery (large tractors, wide implements, where possible p.t.o. driven) is used for tillage. The system is normally based on continuous cultivation.

3.2.2 Tillage systems

Within the cultivation systems, tillage systems can be distinguished. Many criteria can be used to classify tillage systems. The classification used here is based primarily on differences in their effect on soil and water conservation. In principle they can all be applied at different energy-input levels.

Full field, soil invertive tillage

An intensive, full field tillage operation (normally ploughing with a mouldboard or disc plough), carried out in the period between two crops. The arable (tilled) layer is almost completely inverted, burying all material present at the soil surface. This main or primary tillage operation is followed by the creation of a seedbed by secondary tillage operations just before the sowing of the crop. This system results in a weed-free start of the crop with optimum germination/emergence conditions, but therefore leaves the soil with a bare surface for a considerable period of time.
Energy requirement per unit area is high, so this system will seldom be applied with manual labour only, apart from small (garden-type) fields. Since this system is traditionally applied world-wide, it is also referred to as 'conventional tillage'.

Mulch tillage or -farming;

A protective layer of crop residue, live green material or even plastic film is present at the soil surface during the full season or during sensitive (erosion risk) periods. The layer protects against the direct impact of raindrops and in case of overland flow, it reduces the velocity of water. In addition to the physical protection, advantages are: a temperature control at the soil surface, and an improvement of the physical condition of the soil surface (e.g. perforating the crust) by enhancing the activity of soil fauna, like earthworms and termites (Dexter, 1991).

The system is based on mechanical loosening of the topsoil. The prerequisite of material to be present at the surface sets strong limitations and demands to the tillage operations. Special implements have to be used to avoid complete burial of vegetation or residues. Tillage is non-invertive with chisel ploughs with various types of chisels or duckfeet attached, and non-inverting disc implements. Large areas under rainfed farming in semi-arid and sub-humid regions apply some form of mulch-tillage (USA, Canada, Brazil, Australia, South Africa, Mediterranean countries).

The system can be considered as intermediate between the conventional and the no-tillage system. Typical characteristics of this system are given in case 3.

Zero- or no-tillage;

This system also based on the use of mulch, but here all tillage operations, including the seedbed preparation and mechanical weed control measures, are obliterated. Mechanical soil manipulation in this system is limited to the opening of holes or slots in the soil for the placement of seeds. The mulch layer keeps soil organic matter in the surface layer at a high level and in addition attracts soil faunal activity (the most obvious one is by earthworms), which generates an acceptable soil structure. Semi-permanent channels left behind by dead roots and made by worms give a high porosity and in turn a good infiltration rate. These macropores should not be destroyed by tillage. It is only by the strict adherence to this principle that the positive action of the soil fauna is fully exploited.
Abstinence of tillage also rules out the possibility for mechanical weed control. This system therefore implies a strong dependence on herbicides for weed control.

The no-tillage system is characterised by two phenomena: 1. the energy requirement for field preparations is low because of the absence of tillage (although the energy-components of the special planter and the herbicide use are also considerable) and 2. the risk for damage by water and wind erosion is strongly reduced. Typically, no-tillage is applied on larger farms using special, heavy tractor-drawn planters. It is found in the same regions where mulch-tillage is applied.

Although the advantages of the system are well recognised in abovementioned regions, there is a strong controversy about its usefulness and effects on small farms with low external input systems. For South-Sahara Africa, Lal (1977), based on research mainly carried out in (sub) humid West Africa, concludes that the zero-tillage system is the most desirable for reaching a sustainable agriculture. The hypothesis is that the system can be applied under low-input systems, using equipment such as manually operated punch planters and ULV (ultra-low volume) herbicide sprayers powered with batteries or by solar energy.
On the other hand, e.g. Kayombo and Mrema (1994) are quite pessimistic about zero-tillage for small farmers. They feel that still the required levels of mechanization and the expertise of the farmer are too high. Even in countries with rather well-established extension services like Kenya and Zimbabwe, only a very small percentage of the farmers (and these were generally larger farmers) adopted the no-tillage system.
Difficulties with the application of zero-tillage are even more pronounced on SCH soils, where the opening of a furrow or hole for placement of seed is difficult, requiring much energy and often resulting in poor coverage of the seed (poor seed-soil contact).

The amounts of crop residue to act as a mulch are crucial: it was found that stubble-mulch tillage on a clay loam (semi-arid Southern Great Plains, Texas USA) resulted in a better rainfall infiltration than no-tillage, because there was not enough stubble and crop residue to give sufficient protection in order to avoid crust formation in the no-till situation. However, when losses of water by runoff can be avoided, then no-till is more efficient in water use because of a lower evaporation rate (Jones, Hauser and Popham, 1994).

Ridges, tied-ridges;

Ridges (50 to 80 cm apart and 10 to 20 cm high), are very common in the tropics. It is almost an integral component of low energy input systems. Basically, this is a system where the field is left bare after the tillage operation, but since the soil surface is made into a special pattern, the absence of protection is overcome by the high surface storage capacity.
Advantages of the system are e.g.: *savings of energy and labour*, when ridges are left in place, and they are rebuilt each season, only half the field area has to be tilled (otherwise the ridging is an extra expenditure), *improved soil fertility* because all crop residue and other organic material present on the

field surface will be concentrated in the ridge, *water management* due to the fact that when waterlogging occurs it will be in the furrow between the ridges, and because of the possibilities for irrigation, *erosion control* for water when the direction of the ridges is along the contour, and for wind when the direction is perpendicular to the prevailing wind direction, *easier weed control* because ridges allow weeding to be done by animal traction using a ridger.
Ridges along the contour. When the surface of the soil forms of seal or crust, infiltration in the ridge will be reduced and water will collect in the furrow. If the slope of the furrow bottom is zero, water will stagnate and (slowly) infiltrate on the spot. This effect can only be achieved when the ridges indeed follow exactly the contour. It is difficult to construct ridges exactly on the contour, so in practice there is a risk for water collecting in depressions along a furrow, leading to overtopping or breakthrough and causing serious damage.
Tied ridges is a special form of ridging where ridges are 'tied' by crossdams to form basins, preventing water to flow in the furrows. In this way losses of water (and subsequent damage by flowing water) are prevented and thus gives a good water conservation (cf. case 6).
The construction of ridges and crossdams can be done with simple animal draught equipment and therefore this system is well suited for small farmers.

Biamah et al. (1994) compared in a semi-arid area in Kenya three soil management practices: tied ridges, crop residue mulching and conventional tillage. The conclusion (over two rainy periods) was that crop residue mulching gave more moisture in the profile. Tied ridging showed no differences with conventional tillage because the soils showed no runoff. In the absence of residue, conventional tillage leaving large clods at the surface is recommended.

Ridges are not always the best solution to growing crops: Rathore et al. (1983) concluded that in order to improve the emergence of millet under crusting conditions, the crop could be planted on top of the ridges (better cracking pattern). This was on medium textured soils in India. Joshi (1987) found that ridging for light soils and planting in the furrow between ridges was not a good solution (furrow filling up with too much soil). This was also observed during experiments in Mali (Hoogmoed, 1981). Ridges also may cause drier germination conditions (cf. case 4).

Controlled traffic;

Under conventional systems with a high level of mechanization (motorization), the traffic load by the tractors and equipment carrying out the main and secondary tillage operations reduces the beneficial effects of loosening the soil by tillage. This advantage applies to the hardsetting soils in particular, because although these soils show their behaviour after wetting and drying

cycles, additional mechanical forces strongly increase the problems. By separating zones for rooting and traffic, both favourable crop development and timeliness due to improved trafficability can be obtained.
These systems generally include a form of surface configuration like wide beds or micro-catchments. The application is not necessarily restricted to tractorized systems, in the 'broad bed and furrow' system for animal drawn toolcarriers (see next paragraph) the bottom of the traffic lane acts as a drainage furrow.

Special systems; based on a (permanent) surface configuration

The problems associated with SCH soils may also be exploited. In many situations, the total amount of available water (annual rainfall minus losses by runoff and evaporation) may not be sufficient for the growth of a crop. The poor infiltration characteristics can then be used to create areas where water is captured and led to areas where this water can infiltrate. The system of 'water harvesting' is found since ancient times in North Africa and the Near and Middle East.

The SAT where large regions are characterised by high-intensity rainfall, crusted soils and low slopes, has a considerable potential for water harvesting (Reij et al., 1988). Compared to arid regions, the costs of water harvesting, but also the risks of crop failure, are lower, so in the SAT there may be a better economic basis for water harvesting systems, particularly when incorporated in a tillage system.

A number of water harvesting techniques forming part of the regular soil management activities of the farmer are mentioned here (Hudson, 1987).
Microcatchments. These systems consist of depressions excavated on a sloping field with a bordering dike, ridge or bund at the downslope end. In these depressions, water running off along a slope is captured. Typical catchments are V-shaped, 'demi-lunes' (small semi-circular hoops), trapezoidal, square or diamond shaped catchments and collecting areas. The catchments are located in the field in a pattern allowing all water flowing on the surface to be collected. These systems are based on tillage by hand in the depressions.
Pitting. This is a system also based on the formation of depressions, so it is very close to microcatchments. The pits here are smaller and usually have no clear demarcations. There is no clear distinction between catchment and collecting area. Therefore, this is a cross between water harvesting and prevention of runoff losses. The 'zai' system in West Africa is an example of such a system (Vlaar, 1992), in the USA pitting by machinery using cut-out discs or heavy rollers (the 'land imprinter', Dixon and Simanton, 1980) is applied on rangelands. The 'Agwheel' is a similar, recent development

Broad bed and furrow system. This is a system developed in India at ICRISAT, using permanent beds approx 1 m wide with furrows approx. 0.5 m wide laid out in a watershed on a slight (0.5%) slope, allowing controlled runoff. Details of the system are found in Klaij (1983). This system, developed for use with an animal-drawn two-wheeled tool carrier, performs well on Vertisols, thereby allowing a second crop to be grown in the monsoon period. The performance on sealing Alfisols, however, is rather poor due to increased runoff even after small showers. On these red soils, the beds should be rather flat and opened up by tillage in order to prevent excessive water losses (Huibers, 1985). Since the broad bed and furrow system is developed for watersheds with slopes up to 4-5%, the system is not suitable for the West African situation, because of differences in topography (long, slight slopes) and rainfall characteristics (the rainfall in West Africa being more aggressive, as shown in case 1).
W-form ridge and furrow system. This is an adaptation of the broad bed and furrow system and it is developed in the SAT zone of NE-Brazil (Harbans Lal, 1986). Here, a (bare) rainwater harvesting zone consisting of a ridge with a base of 1.5 m is alternated with a planting zone consisting of a ridge of 0.75 m wide. Rainwater collects at the base of the planting ridge. The surface configuration can be made with animal traction or tractors.
Precision strip tillage. This system is developed in Botswana (Willcocks, 1981) on hardsetting and crusting soils. It is based on performing tillage in strips spaced 0.75 m, using a tine mounted on an (animal-drawn) wheeled toolbar. The main reason for this system is a saving of energy for tilling the hard soil, and the construction of a rainwater collecting area (the untilled area in between strips, additionally compacted by the draught animals and the wheels of the toolbar).

3.3. Response to tillage

In terms of soil and water conservation

Choice of the wrong equipment or untimely tillage activities may result in a deterioration of the quality of the arable and rooting layers. It was found that yields of soybean in Brazil were negatively affected by conventional tillage with heavy disc implements. The resultant subsoil compaction and ploughsole formation, caused poor and superficial rooting (Derpsch et al., 1986). Apart from the yield reductions, erosion risk was increased strongly due to the problems in water movement through this compacted layer. A proper choice of alternative tillage activities with chisel ploughs, breaking up the compacted layers and avoiding subsoil compaction gave a better soil and water conservation and showed a savings in energy use (case 3).

In terms of crop yields

The relationship between tillage activities and yield is extremely complex: obvious reasons why there should be a positive effect on yields are: better seed-soil contact in a well-prepared seedbed, improved emergence by breaking up a crust, improved establishment by better water supply because of the destruction or prevention of a seal, better rooting by loosening hard or dense layers in the root zone, and less competition by weeds.

French scientists working in West Africa have reported positive effects of soil tillage on yields of all major crops: an average of 20% increase was found for crops such as millet, sorghum, groundnut, cotton, up to 50% for maize and even up to 100% for rainfed rice (Pieri, 1989, Charreau and Nicou, 1971). This yield improvement is attributed to better rooting, not only in the loosened layer, but also in the deeper layers due to a longer (denser) and finer root network.
In case 4, the effects of tillage on the production of millet under West African conditions are discussed.

conserving soil management and tillage thus reduces the erosion hazard. Under conventional tillage systems, a clean and fine seedbed is required for a successful application of pre-emergence herbicides. A second cause for the occurrence of erosion rills and gullies is the formation of a denser and less permeable layer in the soil profile at a depth of 12-20 cm, as a result of traffic and use of disced implements, working at shallow or medium (<15 cm) depth. The risk for erosion is highest during the preparation and planting period for soybeans in October-November, when rainfall with high intensities may be expected.

The no-tillage or direct drilling system has shown to be the best alternative to avoid erosion losses. This system, however, cannot and will not be used on all farms in Paraná, due to reasons involving capital, farm size, farmers' experience, etc. For those farmers not likely to adopt direct drilling techniques, a conservation-type tillage system may be feasible. One of the methods studied at IAPAR, the agricultural research institute of the State of Paraná is the use of a chisel plough as an 'intermediate' between conventional and zero-tillage systems. Table 18 gives a comparison of the systems.

Table 18. *Summary of tillage systems.*

System	Advantages	Disadvantages
A*	Works always, simple. Good mechanical weed control.	Erosion!!
B	Erosion control. Investments not as high as in direct drilling. Reasonable mechanical weed control.	Performs poorly in large amounts of residue. Chisel plough cannot fully replace other equipment (with discs). Improved drill necessary. Not practical with tractor <40-50 kW.
C	Complete erosion control. Higher yields.	High capital investments. Complete dependance on chemicals. Requires more skill and experience.

A, conventional: disc ploughing or heavy disc harrowing, repeated (up to 5!) disc harrowings, planting with conventional drill (knife coulter), additional chemical weed control (pre-emergence).

B, alternative: chisel ploughing, one disc harrowing (or rotary hoeing), planting with improved drill (disc coulters), additional chemical weed control (pre-emergence).

C, direct drilling: only chemical weed control, planting in harvest residue with special equipment.

In the cropping season 1981-1982, the use of chisel ploughs as an alternative primary tillage operation was assessed. The efficiency of such a system on water erosion control is well known and accepted as a conservation tillage system in the USA (Gupta et al., 1979; Lindstrom et al., 1979; Mannering and Fenster, 1983; Moldenhauer et al., 1983) and has given good results in Paraná

(Sidiras et al., 1982).

The experiments reported here were carried out specifically to find answers to some of the following questions:

- what type of chisel and implement is best suited to replace the disc plough or disc harrow for primary tillage under the conditions prevailing in Paraná?
- what is the effect of using a chisel plough on weed control?
- what are the practical problems involved?

3.4.2. Materials and methods

Tillage equipment

A number of chisel plough models is produced in Brazil, mainly based on the (U.S.A.) type with curved, spring loaded shanks, with various types of interchangeable chisels.

Table 19. *Summary of characteristics of implements used.*

Chisel ploughs

Type	Shank No.	Working width (cm)	Crossbars No.	Crossbars dist.	Furrow dist. (cm)	Frame height (cm)	Shank angle deg.	Chisel angle deg.
A	11	220	4	60	20	69	0	20
B	7	180	3	60	25	71	semi-arc	60
C	7	175	2	73	25	60	45	35
D[1]	9	240	3	81	27	70	arc	45

Other tillage equipment

Type	Working width (cm)	Description
Disc plough	85	3 discs, diameter 68 cm, reversible type
Heavy disc harrow	210	20 (2x10) discs, diameter 61 cm, V-shaped, drawn
Spade plough	256	4 spades, width 30 cm

Tractors

	kW	Weight (kg)	Tyres	Trackwidth (cm)	Used with implement
Ford 6600	60	2484	15-30	142	Chiselplough B and C, disc plough
CBT 1105	78	5300	15-34	168	Chiselplough A and D, heavy disc harrow, spade plough

[1] Drawn; all other implements are 3-point hitch mounted.

In the tests, both Brazilian and European implements were used. The most important characteristics of the implements are given in Table 19 and Fig. 28. One of the purposes of the experiment was to identify the optimum shape or dimension of chisels and shanks, and implement configuration. The best way of testing is to use a standard frame where all parameters can be varied. However, no facilities in this respect were available, thus commercially available equipment was used.

In the main tests, 4 different types of chisel ploughs were compared with the conventional disc plough and the heavy disc harrow and (in one location) a 'spade plough'. A 60 kW and a 78 kW tractor were available for pulling the implements (see Table 19).

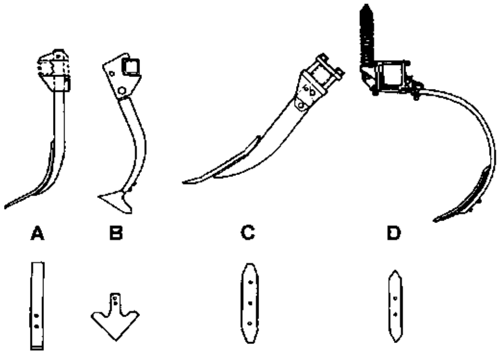


Fig. 28. *Shapes of the chisel plough shanks and chisels used in the experiments.*

Trial site characteristics/soils

Two sites were chosen, one in the immediate vicinity of IAPAR headquarters in Londrina (23°23' S and 51°11' W), and one in the southern region of Paraná, in Vila Velha (25°8' S and 50°10' W).

Londrina (LON)

Soils are described by Kemper and Derpsch (1981); some basic characteristics are given in Table 20. The field used for the experiments was sloping with a gradient of 4-9%. Experimental plots of about 200 x 25 m were laid out allowing tillage operations to be performed along the contour. The field had been under coffee, but for the last 3 years soybean, maize and wheat were grown. The tillage operations were carried out on a wheat stubble.

Vila Velha (VV)

Soils are sandier than in Londrina (Dark Red Latosol, cf. Table 20). This field was situated on a hill and had an irregular shape with slopes up to 10%. Experimental plots had to be laid out following existing contour dams. This field had a long history of annual cropping and was also under wheat stubble.

The soils on these sites, in particular at LON, are difficult to work. The topsoil is very loose, with a bulk density of around 1 g cm^{-3}. The density of the solids was very high, 2.96 g cm^{-3} due to the high percentage of iron oxides. This results in a pore volume of >60%. In addition, the soil tends to adhere strongly to steel

(and other) surfaces of equipment.
These characteristics make it virtually impossible to use implements with a large soil/ tool contact area; investigations (Hoogmoed, 1982) showed, for example, that mouldboard ploughs cannot be used properly on these soils when the percentage of particles <2 μm is higher than 30.

Measurements/determinations

The following parameters were measured:

Before the tillage operations
Soil surface relief, amount of weeds and crop residue at the surface.

During the tillage operations
Working depth, width and speed of the implement; wheelslip of the tractor; time required for turning on headlands; total time required for tilling the plot; fuel consumption; soil moisture content.

Table 20. *Chemical and physical soil analysis.*

	LON	VV
Particle size analysis (%, w/w)		
Clay (<2 μm)	72	43
Silt (2-50 μm)	18	6
Sand (>50 μm)	10	51
Physical characteristics		
Moisture content at field capacity (% w/w)	35.9	26.2
Moisture content at lower plastic limit (% w/w)	34.3	22.3
Dry bulk density (g cm^{-3})	1.10	1.25
Chemical characteristics		
pH H_2O	5.5	5.9
Ca[1]	5.0	4.0
Mg[1]	1.55	1.80
K[1]	0.61	0.33
Carbon (%)	2.3	2.1

[1] me per 100g soil

After the operations

Relief of soil surface and bottom of tilled layer (roughness), amount of weeds and crop residue left at surface; weed control efficiency.
A simple wooden surface reliefmeter (Kouwenhoven, 1979) was used to assess (average) depth of the tillage operation, and the roughness of surface and bottom of the tilled layer. A special technique using permanent stakes was used to measure along the slope (perpendicular to the direction of the tillage

operation) and to calculate depth of work and changes in height of the soil surface. Surface roughness, R, was calculated, with $R = 100 \cdot \log s$, where s is the standard deviation of a series of measurements (Kuipers, 1957). Soil moisture content was determined gravimetrically.

Crop residue and weeds were determined by sampling the above-surface contents on randomly chosen plots of 0.5 x 0.5 m. Weed control efficiency was evaluated on a separate field at LON by determination of the amount of weeds before tillage, shortly after the operation (a few days) and 22 days later, to determine regrowth of the weeds.

Working depth of the implement was determined by the reliefmeter, but also in the field (to adjust the implement) with a probing rod. In the chisel plough tests, depth was determined only in the furrows made by the chisel. Effective width was measured by taking the average of a number of adjacent passes. The travelling speed was determined by measuring with a stopwatch the time required to travel 50 m.

Only total fuel consumption for tillage of each plot of 0.5 ha was measured, since no special equipment was available to measure during runs. Placement of an extension tube on the filler opening of the tank and measurement of fuel temperatures before and after each run reduced the magnitude of errors made in the determination of fuel consumption.

Wheelslip was measured by counting the number of revolutions of the rear wheels of the tractor over the total length of the field.

The performance of secondary tillage and planting equipment was observed on the experimental fields after the tests.

Experimental conditions

Each of the three repetitions of an experiment was carried out in one day, ensuring comparable moisture conditions in the treatments. In LON, the time between repetitions was 6 and 7 days, due to rainfall. In VV, all experiments were carried out within one week, although rain just before the first and before the last repetition caused a difference in moisture content between repetitions. Moisture content of the soil during the tillage operations is given in Table 21.

Table 21. *Moisture content (%w/w) during the experiments.*

Depth (cm)	LON			VV		
	1	2	3	1	2	3
0-5	25.0	23.0	23.5	26.9	18.9	25.0
5-10	32.8	30.4	29.7	26.1	20.8	27.0
10-20	34.1	32.7	32.3	26.4	20.5	25.5

The amount of straw and weeds differed considerably between the two locations. LON had a poor wheat crop as a result of very dry winter weather, yielding only

798 kg straw ha^{-1} and virtually no weeds. The length of the standing stubble was about 10 cm. Weed growth, however, was tremendous in the rainy and warm period between the repetitions.

In VV, more straw and weeds were present (2500 kg straw and weed ha^{-1}) with a stubble length of about 20 cm. At both locations, the straw was chopped by the combine-harvester, so length was no more than 20-25 cm.
All implements were adjusted to reach a depth of 20 cm. This was impossible for the heavy disc harrow, which was set at maximum depth. In a test run, the optimum tractor gear for each implement was determined.

3.4.3. Results

General performance

The heavy disc harrow showed the best ability to work under difficult conditions; the implement cuts through trash and rolls over obstacles. The disc plough performed well on LON, but could not be used in VV, where the resistance of the weeds and straw at the surface was higher than the resistance caused by the soil. As a result, the discs started to counter-rotate. Instead of the disc plough, a locally made 'spade' plough (Fig. 29) was used. This implement is used quite extensively in the southern states of Brazil.

Fig. 29. *The spade plough.*

All chisel ploughs had problems with residue, depending to a large degree on the configuration of the implement. The chisel plough with the widest tine spacing had least problems. The shape of shanks had no great effect, although clearance of Type C was low because of the small angle. The spade plough had less problems with choking because of the large clearances. Choking of the implements not only caused time losses, but also left obstacles at the spots where the implement halted and was cleaned. These hills were difficult to level by subsequent secondary tillage operations.

Fuel consumption

The fuel consumption, shown in Table 22, is expressed in l ha^{-1}, l h^{-1} and m^3 l^{-1}. In LON, consumption per hour is lowest for the disc plough, but highest when expressed per ha, due to the low capacity. The heavy disc harrow yielded opposed values; a high capacity, the lowest consumption per ha and a higher consumption per hour (compared to disc ploughing).This pattern was also found in VV.

Table 22. *Fuel consumption.*

Implement	LON			VV		
	(l ha^{-1})	(l h^{-1})	(m^3 l^{-1})	(l ha^{-1})	(l h^{-1})	(m^3 l^{-1})
Chisel plough A	17.1	14.2	123.2	14.9	13.1	136.0
Chisel plough B	20.2	15.3	87.6	17.2	10.8	96.0
Chisel plough C	17.4	15.2	121.2	14.3	10.7	127.3
Chisel plough D	20.6	14.4	100.3	17.0	12.9	120.6
Disc plough	25.7*	10.0	76.3			
Heavy disc harrow	13.9	12.6	75.9	14.0	13.1	66.0
Spade plough				16.4	12.5	125.4

* Statistically higher (P >0.05)

When the depth is taken into consideration, the differences are even bigger. The various chisel ploughs did not show large differences in consumption. The higher values of Type B are due to the fact that the duckfeet were running right in the compacted layer. Differences were only statistically significant between disc plough and the other implements. It should be realised that the results come from measurements of two different tractors, but each tractor-implement combination used was the best match given the equipment available (see Table 19). The consumption rates are close to values found under comparable conditions in the U.S.A. (e.g. Beppler et al., 1981).

Capacity

Capacities, given in Table 23, range between 0.63 and 0.90 ha h^{-1} for the chisel ploughs, compared to about 0.91 ha h^{-1} for the heavy disc harrow and 0.40 ha h^{-1} for the disc plough. The capacity, clearly, is a function of travel speed, time required for turning around at the headlands (Table 23) and working width. On the narrow strips bordered by contourdams, the three-point hitch mounted implements had a much higher manoeuvrability. The differences in turning time between LON and VV are due to the geometry of the experimental plots within the field. At VV, the headlands allowed much more room for turning around. The travel speed remained rather low, due to fairly high wheelslip values of over 15%.

Table 23. *Performance data of the implement-tractor combinations.*

Implement	LON				VV			
	Cap. (ha h^{-1})	Speed (m s^{-1})	Slip (%)	Turn. time (s)	Cap. (ha h^{-1})	Speed (m s^{-1})	Slip (%)	Turn. time (s)
Chisel plough A	0.83	1.3	15	35	0.90	1.2	16	28
Chisel plough B	0.78	1.5	31	33	0.63	1.1	19	17
Chisel plough C	0.87	1.9	14	30	0.79	1.3	20	21
Chisel plough D	0.70	1.2	21	49	0.76	1.1	23	32
Disc plough	0.40*	1.8	15	27				
Heavy disc harrow	0.90	1.8	11	44	0.93	1.4	14	32
Spade plough					0.81	1.3	14	19

* Statistically higher (P >0.05)

Depth and soil surface roughness

All implements were adjusted to reach as close as possible a depth of 20 cm in the furrow cut by chisels or discs. A more accurate depth calculation was obtained with the reliefmeter data. In Table 24, the average elevation related to the original soil surface is given.

All implements leave a relatively rough surface. At the heavier LON soil the surface left by the disced implements was slightly smoother. At the bottom of the tilled layer there are large differences in roughness; the chisels cut furrows in the compacted layer, but in between the soil remains undisturbed. This explains the difference between the average (measured with the reliefmeter) and the maximum depth (measured in these furrows). In LON, the duckfoot chisels had difficulty in penetrating the dense layer, but on the lighter VV soil it was possible to get below the compacted layer. An example of the differences between the implements is given in Fig. 30 for the LON experiments.

Table 24. *Results of the reliefmeter measurements.*

Implement	LON		VV	
	Depth (cm)	Surface elevation (cm)	Depth (cm)	Surface elevation (cm)
Chisel plough A	16.0	6.1	17.8	5.1
Chisel plough B	13.3	5.7	19.9	4.9
Chisel plough C	15.0	5.6	16.8	7.0
Chisel plough D	14.3	5.1	17.1	5.2
Disc plough	14.5	5.4		
Heavy disc harrow	9.9	2.8	10.9	3.9
Spade plough			16.2	7.7
Roughness *R* after tillage	Surface	Bottom	Surface	Bottom
Chisel plough A	58	44	57	44
Chisel plough B	42	50	61	23
Chisel plough C	50	58	53	57
Chisel plough D	53	66	49	61
Disc plough	40	3		
Heavy disc harrow	41	4	52	7
Spade plough			42	44

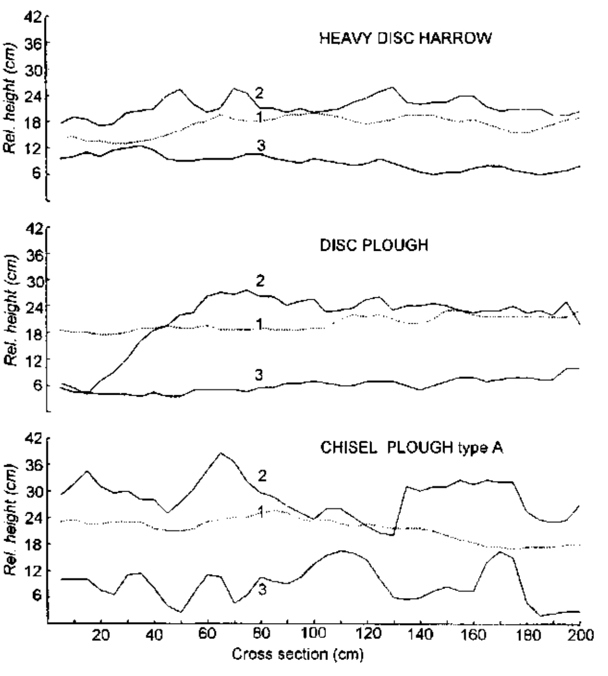


Fig. 30. *Example of reliefmeter results (LON data). 1, original surface; 2, elevated surface after tillage; 3, bottom of tilled layer.*

Crop residue management and weed control

A certain percentage of the crop residue (straw and standing stubble) and weeds (green) will be buried by the tillage operation. In Fig. 31, the results for both LON and VV are given. The disced implements leave a relatively small percentage of residue and weeds at the surface, ranging from 30 to 50%, compared to the chisel plough leaving 70-85% in LON, and 50-65% in VV at the surface. The differences between VV and LON were mainly caused by the differences in soil conditions.
The percentage of material left at the surface by the chisel plough is not a good indicator of weed control efficiency. Soon after the tests, the fields were planted. No differences in weed population were observed during growth of the soybean crop. Fig. 31 shows the results of an additional experiment carried out to determine weed control efficiency of the four chisel ploughs. Chisel plough Type B with duckfoot chisels gives the best results, closely followed by chisel plough Type A with the narrowest furrow distance. Types C and D, with narrow chisel and a furrow distance between 25 and 30 cm, have the poorest weed control.

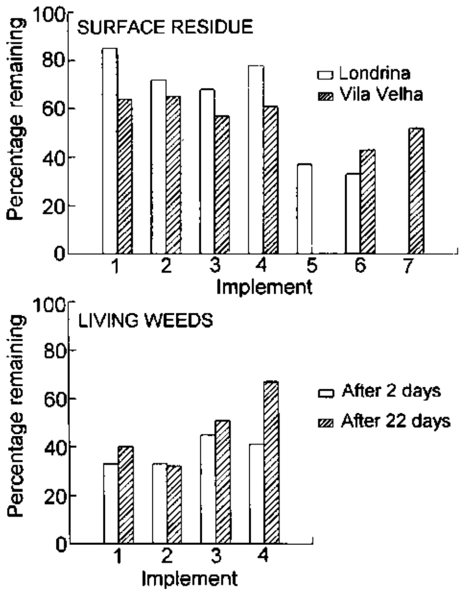


Fig. 31. *Residue management and weed control. 1, 2, 3 and 4, chisel plough types A, B, C and D; 5, disc plough; 6, heavy disc harrow; 7, spade plough.*

3.4.4. Discussion

Although four clearly different types of chisel ploughs were used, there was not one specific type that did a much better or worse job. The fuel consumption was lower compared to disc ploughing, and slightly higher than heavy disc harrowing. The capacity was higher than the disc plough and slightly lower than the heavy disc harrow, although difficulties with choking must be taken into consideration. The construction of the frame and placement of shanks and chisels had a very big effect on the flow of material through the implement. The distance between shanks (in all directions) should be at least 60 cm; height of the frame (= distance between tip of chisels and frame) should be 75 cm to ensure a sufficient clearance.

To function properly, in particular in terms of weed control, a chisel plough should be able to work uninterrupted at a speed of at least 8 km h^{-1} (Krause et al., 1984). The weed-killing action of a chisel plough is the result of two phenomena: cutting and pulling out of roots and burying of plants. When duckfoot chisels are used, cutting is the main action, but for narrower chisel types the disturbance of the soil, which can only be obtained at a certain minimum speed, is more important. Although the power was available in our experiments, repeated halting due to implement choking caused the speed to remain too low.

Working conditions in spring on the wheat stubble fields proved rather difficult. This is typical for Paraná; the weather is warm and moist, so weed growth conditions are favourable. This implies that when a farmer is not able to start chiselling operations immediately after harvest (e.g. due to rain), weeds may render use of the chisel plough impossible within 2 weeks, and disced implements have to be used.

The larger amounts of residue on the surface caused problems in subsequent operations; use of a planter with shoe coulters was impossible on the chisel ploughed fields, even after seedbed preparation with a light disc harrow. A planter with a fluted disc furrow opener performed satisfactorily.

3.4.5. Conclusions

Use of chisel ploughs in Paraná faces a number of difficulties. It was found that the strongly adhering soil and the large amount of weeds in the spring easily causes blocking of the implement. This implies that, unless technical solutions to this problem are found, the chisel plough cannot fully replace the disc plough or heavy disc harrow.

On the other hand, in addition to the improved erosion control, chisel ploughing uses less fuel than disc ploughing (per ha) and is more efficient per volume of soil manipulated than heavy disc harrowing, and can be carried out with a capacity only slightly lower than heavy disc harrowing and higher than disc ploughing.

When use of a chisel plough is considered, the following points are important: a wide shank spacing (>60 cm) and a proper frame clearance (>50 cm when engaged in the soil) should be combined with a furrow distance of around 20 cm. This can be achieved only by using a frame with four cross-bars. Narrow chisels are recommended over duckfeet under these conditions. Apart from this, shape and dimensions of shanks and chisels are not important. Three-point hitch mounted implements are easier to use than drawn implements, in particular on narrow strips of land. Sowing equipment must be adapted to cope with larger amounts of crop residue on the surface.

3.5. Case 4. Soil management for crop production in the West African Sahel

3.5.1. Introduction

This case follows case 2 and also deals with soil and crop management options for increasing crop production in the Sahelian agro-climatical zone. In case 2, soil parameters of the sandy soil (Psammentic Paleustalf) of ICRISAT's Sahelian Center (ISC) near Niamey, Niger were described. Climatic parameters across Niger were also analysed. These two parameters have important soil and crop management implications.
Seasonal, high intensity rainfall, high temperatures, and physically and chemically poor soils commonly result in poor crop stands and yield of pearl millet. Early sowing is important as each week of delay in sowing advances the heading date by 1 day, potentially decreasing yields (Kassam, 1976). The method of sowing and seed quality are also important factors (Soman et al., 1987). How these factors interact in affecting stands, and the best tillage and sowing technique depend largely on the soil and location.

Farmers' sowing practices

A study of some of the factors affecting establishment was carried out in the Niamey region in the early season of 1985 (ICRISAT, 1986; Soman et al., 1987). Farmers sow immediately following rain without prior tillage. With a long handled hoe planting holes are made, into which a variable number of 40-300 seeds are deposited (hill). Subsequently, the soil is pushed back and compacted by foot. As a result, sowing depth varies, both within and between fields, ranging from 2 to 8 cm. The number of hills varies from 3500 to 11000 ha^{-1}. Although standard laboratory germination of the seeds used was good (over 80%), average emergence was only 25%. Low seedling emergence should not be a problem provided the surviving seedlings produce grain. However, a generally dry period followed, and post-emergence death of seedlings reduced otherwise adequate stands. Stands declined on average from 4900 to 2300 hills ha^{-1}, and stand failure was noted in nearly half of the fields studied. This was attributed to high soil temperatures, rather than to low soil water content (ICRISAT, 1986).

Seed factors

Field emergence rates are positively related to seed size (Lawan et al., 1985), but even in the best circumstances on-station seedling emergence rates range typically between 32 and 40% (ICRISAT, 1987). According to Stomph (1990), differences between the emergence rates of different genotypes are easily blurred by variable environmental conditions during the growth cycle, seed processing, and storage of the seed.

Environmental factors

Early storms are often accompanied by strong winds. Wind speeds exceeding 100 km h^{-1} have been recorded at ISC (Sivakumar, 1989). Blowing sand subjects seedlings to abrasion, and often results in their being completely covered by sand, causing serious problems in crop establishment. When there is insufficient crop residue to protect the soil surface, 'emergency tillage' practices must be used to provide protection (Fryrear, 1969). The principle is to create a rough and cloddy soil surface. When such clods are not produced, or easily disintegrate, ridging may be the only effective method of roughening the soil surface (Fryrear, 1969). Wind tunnel studies have shown that under such circumstances, ridges 127-248 mm in height were most effective and reduced soil erosion rates by 85% (Fryrear, 1984). Under moist conditions relatively stable clods can be formed by tillage (case 2). An alternative emergency tillage tool used to quickly roughen the surface of sandy soils is called a 'sand fighter'. This consists of an axle, with radial tines, which when pulled over the surface creates small depressions and clods in wet soils. Sand fighting has to be repeated after each rain event (Fryrear, 1969).

Soil compaction

Poor crop performance may also result from poor rooting due to soil compaction, and from reduced rainfall infiltration due to crusting. Remedial mechanical loosening of the soil is then necessary (Charreau and Nicou, 1971; Lal, 1989). Extensive tillage research in semi-arid West Africa indicates the beneficial effect of reduced soil bulk density on root proliferation of groundnut, sorghum, maize and upland rice (Blondel, 1967; Nicou, 1974; Nicou and Charreau, 1985), and even of millet in sandy soils (Chopart and Nicou, 1976). Chopart (1983) reports a doubling of root dry weight of millet in a ploughed sandy soil compared with no-till, during the first 50 days. Strong positive correlations between the reduction of soil bulk densities, root growth, and yield have been reported for many crops of the region (Charreau and Nicou, 1971). Millet grain yields are reported to have increased by 22% on average as a result of tillage from a total of 38 experiment years (Nicou and Charreau, 1985). When tillage is combined with fertilization and the use of crop residues, ploughing improved soil productivity and crop yield with time, even in the driest years (Pieri, 1985).
Although not a problem at the ISC, some sandy soils in the Sahel under millet are sensitive to crusting and seriously impede infiltration (cf. case 1). For such soils, tied ridges improve infiltration (cf. case 6), and with the use of this technique increases of millet and sorghum yields of 340% have been achieved (Perrier, 1987).

This case reports a series of field experiments carried out in a sandy soil typical of millet fields in Niger. The experiments were designed to evaluate (interaction) effects of seed size, depth and method of planting, millet variety, tillage, and soil fertilization on emergence, establishment, and yield of pearl millet.

3.5.2. Materials and methods

Experiment 1: *Field emergence and establishment as affected by seed size, sowing depth, and variety.*

The effects of seed size and depth of planting on field emergence and establishment of two improved (cv.'CIVT', and cv.'3/4 HK') and one local millet variety (cv. 'Sadoré local') were studied in the 1985 rainy season. The improved seeds were certified, the local variety seeds were taken from the previous year's bulk harvest.

Laboratory measurements

Small (less than 1.95 mm), medium (1.95-2.12 mm) and large (more than 2.12 mm) seed fractions were obtained using standard wire mesh sieves.
Thousand grain weight and germination for each variety and seed size were determined in four replications. Seeds were placed in petri dishes on moistened filter paper. Germination was considered successful when a radicle and plumule appeared. Germination, determined after 3 days, was expressed as a percentage of the total number of seeds.

Field measurements

The design was a randomized block full factorial experiment with five replications. Planting depths were 1, 3, 5 and 7 cm. Each sub-plot consisted of a single 5 m row. Row spacing was 0.75 m. Within-row hill spacing was 0.5 m. The seeds were sown in hills after 15 mm of rain on a flat, hand hoed field. The hill planting system was as follows: a hand held, thin walled hollow tube (5 cm diameter) was used to extract the moist soil to the required depth. Forty seeds were then emptied into the hole, and the soil core put back in its original position. No fertilizers were applied.
Crop emergence was evaluated in terms of percentage of hills emerged at 5, 8 and 17 days after sowing (DAS). A hill was considered emerged when at least three seedlings were present. In addition, emergence was determined by counting all seedlings at 10 DAS. Establishment was evaluated in terms of average seedling dry matter per hill, and the number of secondary roots per seedling, both determined at 24 DAS from three to five hills per sub-plot.
There was 1 mm of rain at 3 DAS followed by 30.3 mm at 4 DAS, 34.2 mm at 5 DAS, and 6 mm at 11 DAS. The maximum soil temperature at 1 cm depth was 46.7 °C, measured at 3 DAS.

Experiment 2: *Effect of sowing method and fertilization on establishment and yield.*

Two sowing methods, sowing in hills (comparable to the traditional method), and drilling seeds were compared at two fertility levels during the 1984 rainy season in a randomized block factorial experiment with four replications. 'Sadoré local' was sown using a tractor-mounted four-row unit planter. The planter was modified in-house in two ways. Each unit was fitted with a cone seed metering system. The system enables a uniform flow of a given amount of seed into the furrow over the length of the plot. In addition, the bottom end of each seed tube was fitted with a solenoid activated valve. In the hill-sowing mode the valves are closed, so that the metered flow of seeds accumulates at the bottom of the seed tube. The valves open momentarily after a set distance travelled, releasing seeds into the furrow, over a short (0.10-0.15 m) interval. This insured, independently of the sowing mode, a consistent seeding rate and depth (3-4 cm), as well as uniform packing. Where hills were sown their distance in the row was set to 1 m. Fertilizer rates were: (i) no fertilizer added; (ii) 17 kg ha^{-1} of P (as triple superphosphate) before sowing plus 40 kg ha^{-1} of N (as calcium ammonium nitrate) in a split application 2-3 and 4-6 weeks after sowing. Plots consisted of 12 rows 20 m in length and 0.75 m apart.
Crop stands were measured at 3 and 13 DAS. Plant height was measured at 13 DAS. Two weeks after sowing the crop was thinned to three plants per hill and a corresponding three plants m^{-1} in drilled rows. The crop was allowed to mature, and grain yields were determined.

Experiment 3: *Effect of primary tillage, fertilization, and variety on establishment and yield.*

The effect of tillage before sowing and fertilization on crop emergence, establishment and yield was evaluated during the 1984, 1985, and 1986 rainy seasons. The design was a randomized block factorial experiment with four replications. The following four tillage treatments were compared:

(i) ploughing to a depth of 0.15 m (using a Massey Ferguson Model 765 disc plough[12] fitted with three discs);
(ii) ridging without prior tillage (using a John Deere 984 integral four-row bedder with staggered discs set to a ridge spacing of 0.75 m and ridge height of 0.15 m);
(iii) 'sand fighting' (using an in-house 3-m-wide sand fighter);
(iv) a no-till control.

Plot size was 9 m x 20 m. Tillage was executed yearly, after the first rain event

[12] Trade names do not constitute endorsement of or discrimination against any product by ICRISAT or WU.

in May or June that exceeded 8 mm. Sand fighting was repeated during crop establishment using a 0.6 m-wide animal drawn sand fighter between rows after any significant rain. Annual fertilizer rates and timing of application were identical to those of Experiment 2. Phosphorus was applied before tillage. In 1984, 'Sadoré local' was hill planted at a depth of 3-5 cm with 1 m between hills in rows spaced at 0.75 m, perpendicular to the prevailing (easterly) direction of erosive winds.
Improved millet varieties ('CIVT' and '3/4 HK') and residual fertility effect were added as treatments from the second year. Fertilizer sub-plots were split after the first year to assess the residual effect of fertilization. Tillage and fertilizer treatments remained permanently assigned to plots. The crop was thinned to three plants per hill about 3-4 weeks after sowing. Weeding was done by hand twice per season. No crop protection measures other than bird scaring were taken.
Emergence and stand survival in terms of percentage of hills sown were measured at various dates during the crop cycle. Daily total rainfall was also measured. To assess the stability of effects of tillage and fertilization over the years, a combined analysis of data over the years 1985 and 1986 was made. The year 1984 was not included because of the additional treatments executed in that year. Crop stands at harvest, grain yield per hill harvested, and total grain yield were analysed.

Experiment 4: *Effect of primary tillage, fertilization, variety, and residue management on establishment and yield.*

This experiment, performed during the 1985 and 1986 rainy seasons, included the same factors as Experiment 3, but with larger plots. This was done because the possible beneficial effects of wind erosion control measures due to tillage could have been masked owing to border effects in the smaller plots used. The experiment was a split plot with three replications, with tillage assigned to main plots 30 m x 30 m in size. The first split was assigned to fertilization, the second to variety and the third to crop residue management. Tillage and fertilizer treatments were identical to those of Experiment 3. The local variety, 'Sadoré local', was compared with 'CIVT'. Crop residue management compared mulching of millet stalks with the removal of crop residues. All treatment combinations were permanently assigned to plots.

In the first (1985) rainy season, after sowing, millet residues were added at a rate of 4 t ha^{-1}. In 1986 the residue of the 1985 crop was used as mulch. As a result of the tillage treatment, these residues were incorporated in ploughed plots, partially incorporated in the ridged plots, anchored in the sand-fought plots, or left on the surface in no-till plots. Weeding operations were identical to those for Experiment 3. No crop protection measures other than bird scaring were taken. Initial crop stand (measured at 16 DAS in 1985, and 18 DAS in

1986), crop stand at harvest, and grain and stover yields were evaluated. A combined analysis of data over the 2 years of the experiment was made.

3.5.3. Results and discussion

Experiment 1: *Establishment effects of seed size, sowing depth, and variety.*

Laboratory measurements

Germination is shown as a function of thousand grain weight in Fig. 32. Germination varied with variety, with '3/4 HK' having good germination for the three seed sizes. Germination of 'CIVT' and 'Sadoré local' was lower, and decreased with seed size, particularly for the local variety.

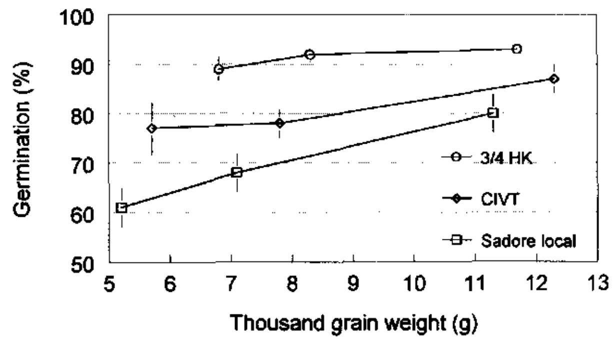


Fig. 32. *Relationship between thousand grain weight and laboratory germination of three seed fractions for three millet varieties. Vertical bars indicate standard errors of germination. Standard errors of thousand grain weights are less than 0.46 g.*

Field measurements

Depth of sowing was the only significant effect on the percentage of hills emerged, for all dates measured. Maximum hill emergence was observed at 8 DAS. At 17 DAS, stands had somewhat declined with significantly lower stands for the smallest seed size. No interaction effects occurred at any of the three dates (Table 25).

Seedling emergence at 10 DAS was significantly ($P<0.001$) affected by depth of sowing, seed size, and variety (Table 26).

Table 25. *Effect of sowing depth and seed size on emergence of hills in the 1985 rainy season.*

Treatment	Emergence (% of hills sown)		
	5 DAS	8 DAS	13 DAS
Depth of sowing (cm)			
1	85.1	86.2	84.2
3	91.6	92.4	90.4
5	93.1	94.0	90.7
7	91.3	90.7	86.7
SE	±1.7	±1.6	±1.7
Seed size			
Big	91.5	91.2	90.5
Medium	91.7	90.8	89.5
Small	87.7	90.5	84.0
SE	±1.4	±1.4	±1.5
CV (%)	12	12	13

Table 26. *Effect of depth of sowing, seed size, and variety on seedling emergence at 10 DAS (percentage of seeds sown), shoot weight at 24 DAS, and number of secondary roots per seedling at 24 DAS, 1985 rainy season.*

Treatment	Emergence (% seeds sown)	Shoot dry weight (g per hill)	Secondary roots (no. per seedling)
Depth of sowing (cm)			
1	43.0	2.85	3.30
3	51.4	3.77	3.17
5	52.7	3.92	3.21
7	45.6	2.92	3.05
SE	±0.4	±0.24	±0.07
Seed size			
Big	54.0	5.11	3.51
Medium	50.6	3.15	3.11
Small	39.9	1.82	2.91
SE	±1.2	±0.21	±0.06
Variety			
' 3/4 HK'	56.4	3.35	3.00
'CIVT'	48.0	3.85	3.36
'Sadoré local'	40.0	2.89	3.18
SE	±1.1	±0.21	±0.06
CV (%)	19	49	15

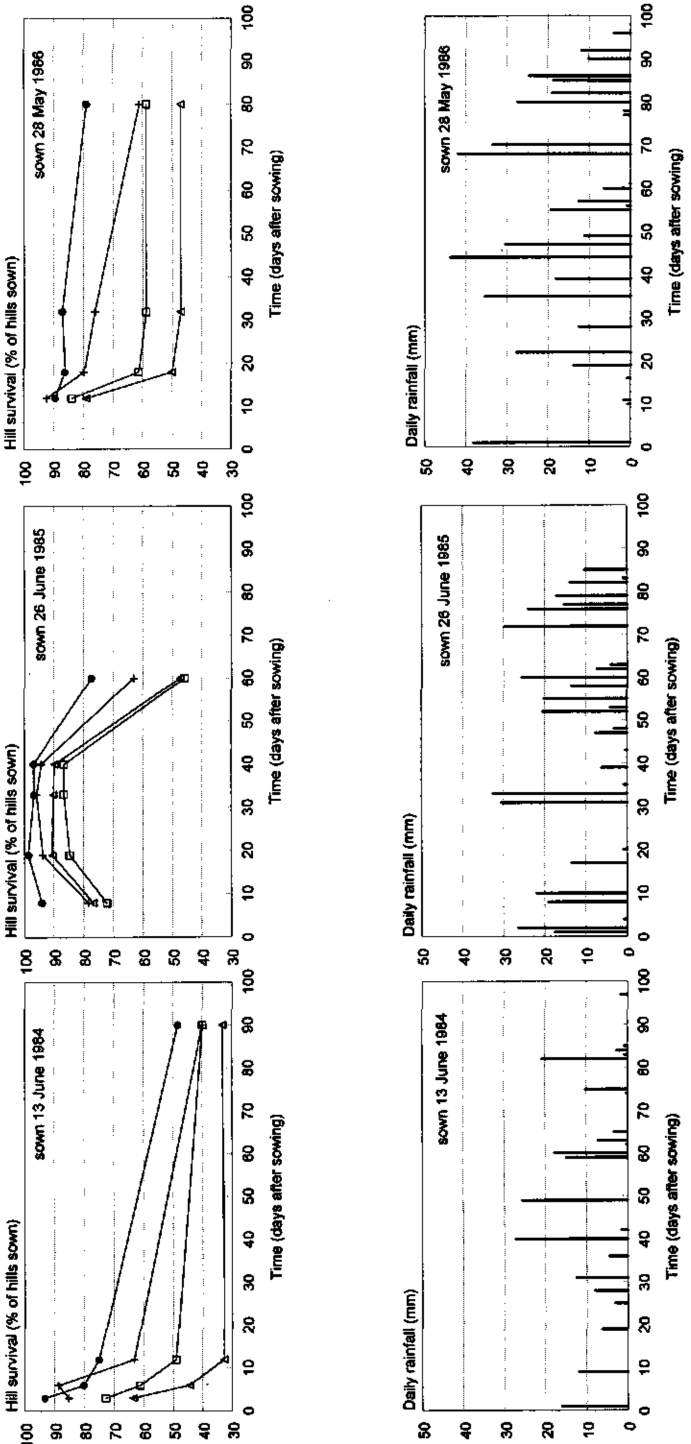
There was a small but significant ($P=0.022$) seed size by variety interaction, with emergence dropping off for the small seed fraction of 'Sadoré local' (data not shown), similar to the laboratory results. Seedling shoot dry weight was significantly affected by sowing depth, variety ($P<0.01$), and seed size ($P<0.001$). A similar small significant seed size by variety interaction as observed with seedling emergence was present (data not shown). The number of secondary roots was independent of sowing depth, but seed size increased the number of secondary roots significantly ($P<0.001$). Variety also affected roots, with 'CIVT' having the most roots ($P<0.001$).

The highest percentage of hills initially emerged and survived for the intermediate sowing depths. Intermediate depth of sowing produced on average 52% seedling emergence, thus significantly outperforming shallow and deep sowing. A similar apparent optimum sowing depth of 3 cm for two millet varieties in a sandy soil is reported by Hoogmoed (1981). Seedling emergence from both the shallowest and deepest sown seeds was inferior to those of the intermediate sowing depths, and had also the lowest shoot mass. Some removal of freshly sown seeds by ants and rodents was observed, the latter continuing to dig up young seedlings. This could account for the inferior performance of the shallow sown seeds. Rainfall distribution resulted in good soil moisture availability and prevented the build-up of sustained high soil temperatures. The maximum soil temperature at a depth of 1 cm occurring at 3 DAS was 46.7°C, well below temperatures reported by Soman et al. (1987) of 51 ± 3.2°C after 12 days of dry weather. It is suggested that, for the deepest planted seeds which emerged only half a day later, more of the nutrient reserve contained in the seeds was depleted, leaving the seedling in a weaker condition at emergence.

Experiment 2: *Effect of sowing method and fertilization on establishment and yield.*

Emergence was higher in drilled plots than in hill planted plots, but early survival and development of seedlings were inferior. Two storms occurring between 3 and 13 DAS with high wind speeds produced ideal conditions for wind erosion. Average millet seedling stands at 13 DAS in drilled plots dropped from 198 000 to 134 000 seedlings ha^{-1}. The average total number of seedlings in hill planted plots was 107 000 ha^{-1}, while the number of hills dropped by 9% to an average of 10 400 hills ha^{-1}. However, maximum seedling height in hills was 16.9 cm, significantly greater than the height of 10.2 cm observed in drilled rows (SE ±0.86). Possibly because of temperature effects and sand blast protection of the innermost seedlings, growth conditions for surviving seedlings in hills had been more favourable. There were no fertility, nor fertility by sowing methods effects during this stage.

From sowing until harvest only 190 mm of rainfall was received. Yields and yield responses to treatment factors were therefore low. There were no significant sowing method by fertilization effects. However, the grain yield of drilled seeds (0.27 t ha^{-1}) was significantly lower than that of hill sown seeds (0.34 t ha^{-1}) (SE ±0.031). The use of fertilizer increased yields from 0.25 to 0.36 t ha^{-1} (SE ±0.031).



Top: Percentage survival of 13 300 hills ha^{-1} sown over time, for the rainy seasons of 1984, 1985, and 1986. No-till □, sand fighting Δ, ridging +, ploughing ●. Vertical bars indicate standard errors. Bottom: daily rainfall

Fig. 33. *The effect of tillage on average pearl millet stands*

Experiment 3: *Effect of primary tillage, fertilization, and variety on establishment and yield.*

Three consecutive seasons were quite different in terms of storm frequency, characteristics, and total rainfall received. The effects of tillage on crop stands are presented in Fig. 33. In 1984, the first rain-bearing storm occurred at 9 DAS and a second at 19 DAS. Both storms were characterized by high winds, in both cases blowing over an already dry soil surface. The resulting sand blasting reduced crop stands markedly. In 1985, during the 20 day period following sowing, there were five storms, all much less violent in terms of wind. As a result of the wetter topsoil and reduced erosive force of the wind during the storms, conditions for crop establishment were most favourable of the 3 years studied. In 1986, no substantial rains were received until 17 DAS. However, a series of highly erosive wind storms occurred at 10, 11, and 16 DAS. Because the soil surface was dry by then, wind-blown sand caused a considerable decline in stands. Common to all years is the consistent and significant effect that tillage had on early stands. Ploughing and ridging produced the best stands. Also common was the fact that neither fertilizer nor its interaction with tillage significantly affected early crop stands.

Table 27. *Tillage and fertilization (interaction) effect on pearl millet stand at harvest (percentage of hills sown), grain yield per hill, and total grain yield, average of three millet varieties, average for the rainy seasons of 1985 and 1986.*

Treatment	Hill survival (% hills sown)			Grain yield (g per hill)			Grain yield (kg ha^{-1})		
	F0	F1	Mean	F0	F1	Mean	F0	F1	Mean
Ploughing	67.9	87.4	77.6	25.3	57.4	41.4	254	681	467
Ridging	43.5	80.4	61.9	24.4	57.6	41.0	180	649	414
Sand ft.	30.6	63.1	46.8	22.0	37.2	29.6	89	352	220
Zero-till	41.8	63.2	52.5	18.6	42.0	30.3	139	402	271
SE	±3.2			±5.1			±40		
Mean	45.9	73.5		22.6	48.6		165	521	
SE	±1.4		±2.5	±2.3		±3.9	±15		±33
CV(%)	33			56			60		

F0, no fertilizers applied; F1, fertilizers added.

The low rainfall received in 1984 masked the earlier stand advantages gained from tillage. Only the addition of fertilizer increased crop grain yield from 0.28 to 0.39 t ha^{-1} (SE ± 0.031). Average results for crop stand at harvest, grain yield per hill and grain yield ha^{-1} for 1985 and 1986 are presented in Table 27. The year by management tillage and fertilization interactions were not significant, indicating the consistency of the effects of these treatments. The tillage by fertilization interaction was significant ($P<0.05$) for crop stands and grain yield ha^{-1}. On non-fertilized plots, crop stands were best assured by ploughing, resulting in the highest grain yield ha^{-1}. Fertilization was the single most important factor increasing grain yield per hill.

Allied with superior hill survival following ploughing or ridging, yields almost doubled when compared with sand fighting and no-till. Varietal differences in grain yield were significant, average grain yields were 0.22 t ha^{-1} for '3/4 HK', 0.40 t ha^{-1} for 'CIVT', and 0.41 t ha^{-1} for the local variety. The residual effect of fertilization was limited to crop stand survival, with average stands increasing from 56 to 63.4% (SE ± 1.75).

Table 28. *Effect of tillage, millet variety, fertilization, and crop residue on plant population (percentage of 13 300 hills ha^{-1} sown) and crop yield components. Average for the rainy seasons of 1985 and 1986.*

Treatment	Crop stand (% of hills sown)		Crop yield (t ha^{-1})	
	Initial	Harvest	Grain	Stover
Cultivation				
Ploughing	72.2	72.2	0.591	1.94
Ridging	79.7	69.9	0.518	1.71
Sand fighting	51.1	43.6	0.200	0.89
Zero-till	51.1	39.8	0.221	0.78
SE	±5.0	±4.2	±0.079	±0.19
CV(%)	1.9	1.8	5.1	34
Variety				
'CIVT'	69.9	59.4	0.354	1.01
'Sadoré local'	57.1	54.9	0.412	1.66
SE	±1.9	±1.2	±0.014	±0.04
CV(%)	2.1	1.5	25	20
Fertilization				
No	58.6	46.6	0.195	0.69
Yes	68.4	66.2	0.570	1.97
SE±2.3	±2.0	±0.033		±0.16
CV(%)	1.8	1.7	42	32
Crop residue				
Removed	61.4	54.2	0.366	1.25
Left	65.7	58.6	0.399	1.41
SE	±1.7	±1.2	0.018	±0.05
CV(%)	26	20	46	39

The positive effect of ploughing and ridging on early stands probably arises from reduced soil bulk density which is conducive to root proliferation. The addition of fertilizer contributed to more vigorous and sustained growth in the hills that survived. The advantages of tillage over no-till might be offset by a delay in sowing. However, Hoogmoed and Klaij (1990) calculated for the Niamey region that there was a 40% probability of receiving a first storm sufficient for 2.3 days of tillage, but unsuitable for planting.

For the years in which this did not occur, possible yield advantages from no-till associated with early sowing would likely be partly nullified, as stands and stand survival would probably be in this case equally affected by environmental conditions, while foregoing the more vigorous growth per hill resulting from tillage. The considerably larger plots used for tillage in this experiment, compared with Experiment 3, did not alter its effects on crop stands and yield (Table 28). Results were quite similar to those found in Experiment 3.

Experiment 4: *Effect of primary tillage, fertilization, variety, and residue management establishment and yield*

The year by tillage or fertilization effect was insignificant, indicating the consistent performance of tillage and fertilization treatments. However, there was no statistically significant tillage by fertilization interaction effect. Crop stands, determined after sowing and at harvest, confirm the significant positive effect that ploughing or ridging had on initial stands and their survival. In contrast to Experiment 3, fertilization also improved initial stands.

Crop yields were significantly affected by fertilizer application and tillage. Fertilization increased crop grain and stover yields almost threefold. Ploughing or ridging improved yields threefold over the sand fight and no-till treatments. As in Experiment 3, stands accounted for only part of the improved crop production brought about by tillage and fertilization.

The use of crop residues showed a significant treatment by year interaction, possibly resulting from a cumulative amelioration of soil conditions over time. Crop stover yields in 1985 were 1.04 t ha^{-1} on plots without crop residue, and 0.98 t ha^{-1} on plots with crop residues left. In 1986, these yields were 1.46 t ha^{-1} and 1.85 t ha^{-1} respectively. Grain yields also responded significantly (data not shown).

The local variety had significantly higher grain, and stover yields than 'CIVT'. The much larger plots used did not improve the performance of sand fighting over no-till; the clods produced by sand fighting were not sufficiently stable to reduce the wind erosion hazard in this case.

3.5.4. Conclusions

Seed size, sowing method and depth improved emergence and establishment of pearl millet substantially. For the sandy soil studied, an optimum sowing depth of 3-5 cm was found. Hill sowing was far superior to drilling in terms of seedling survival and crop yield. With the indigenous hill sowing method, a fair portion of the seeds sown will fall within the optimum depth band. Selecting the biggest

seeds, and maintaining the proper sowing depth requires skill only on the part of the farmer. Whether or not these crop establishment advantages ultimately lead to yield increases depends on other factors such as soil fertility management and tillage.
A total of six experiment years on replicated factorial experiments show the consistent advantage that modest doses of P, and N fertilizers together with tillage have on pearl millet production. Crop establishment improves, stands at harvest are better assured and yield per hill is much higher. Application of chemical fertilizer consistently increased millet grain and stover yields about threefold in close to normal years, while a 50% increase in grain yield was obtained in the driest year on record. These substantial gains are realized by a scale neutral input. Grain and stover yields on non-fertilized plots were increased two- to threefold by ploughing or ridging before sowing, and sixfold when fertilizer application was combined with tillage.
The tillage methods used, particularly ridging, can well be carried out by animal traction. In the Niamey climatic region, advantages of tillage not offset by delayed sowing can be expected in 4 out of 10 years.

4. MODELLING TILLAGE INTERACTIONS

4.1. Models and tillage

Modelling has become a generally accepted tool in agricultural research and decision making. In the discipline of soils, water and crops, a large number of models has been developed. Models related to *tillage* and *soil and water conservation* can roughly be divided into the following types:

(1) dealing with water in the soil: infiltration, movement and storage, availability
(2) simulating plant and crop growth, development and production
(3) addressing energy and time requirements and expenditure (for soil tillage)

In Table 29, a listing is given of models developed for the simulation of runoff, erosion and crop growth and yield, based on (a.o.) input of climate, soil and management. This listing does not claim to be exhaustive: in view of the wealth of models currently available, creating such a list would form an impossible endeavour. In particular for the simulation of crop growth and yield many more models can be mentioned, but in these models the (direct) effect of soil management or soil structure is negligible. A discussion on crop models for semi-arid regions is given by Ritchie (1991), and registers of agro-ecosystems models are currently kept on Internet sites[13]. In the table information is given with respect to what processes are calculated or used in the simulation and what methods are used to calculate water movement. It is also indicated which 'type' the model represents. Broadly, the following types may be distinguished (adapted from Rabbinge and van Ittersum, 1994).

With respect to calculation:
Stochastic or functional (S): Simple functions, based on empirical or 'estimated' physical processes. Results in terms of probabilities or likely results.
Deterministic or mechanistic (M): Complicated functions, closely describing physical processes. Inputs from parameter values such as K-ψ and ψ-θ.
With respect to spatial applicability:
Lumped (L): Generally one-dimensional: simulation on point or plot scale, no spatial variability
Distributed (D): Aggregation of elements simulated by 'lumped' models: represents spatial variability (e.g. field or watershed).
Thus models can be a combination of *S* or *M* with *L* or *D.*

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[13] Sites a.o. at Wageningen University (www.bib.wau.nl/camase) and Kassel, Germany (dino.wiz.uni-kassel.de/ecobas.html)

Table 29. *Soil-water-crop and runoff-erosion models*

nr	name	type	functions	surface layer simulation	water movement	tillage and/or other farming components
1	RUSLE	SL	D,E	n.a.	n.a.	tillage is part of C (crop management) factor
2	SLEMSA	SL	D,E	n.a.	n.a.	tillage practices influence soil erodibility factor
3	GUEST	SL	D,E	n.a.	n.a.	detachability of tilled or untilled soil
4	APSIM-SoilWat	SL	A,C,D,F,G,H,I,J	CN or SWIM	as in SWIM	tillage, crop residue management, weeds
5	CREAMS	SL	A,C,D,G,	CN, Rit	SR	tillage influences C factor (as in RUSLE)
6	CROPSYST	SL	C,G,H,I	CN, EB	SR	input data sets for different tillage systems
7	EPIC	SL	A,C,D,G,J	CN, Rit	SR	is part of management input
8	GLEAMS	SL	A,C,D,F,G	CN, Rit	SR	tillage effect on C (RUSLE)
9	PERFECT	SL	A,C,D,H,I,J	CN, Rit	SR	tillage modifies sealing and crusting parameters
10	SPAW	SL	A,B,C	CN, simple	Darcy	indirect
11	MAX 0.34	SL	E,I	n.a.	n.a.	economic evaluation of farming
12	Soil_Depl	SL	D,I	n.a.	n.a.	long term management systems (incl. tillage)
13	SARRA	SL	A,B,H,I	n.a.	SR	tillage in management input
14	BIPODE	SL	A,B,C	n.a.	SR	crust status governs infiltration
15	SWAT	SD	A,C,F	CN, various	SR	extended and improved version of SWRRB
16	SWRRB	SD	C,E,G	CN, Rit	SR	distributed version of CREAMS
17	ANSWERS	SD	A,D,E,F,G	Kmax	SR	surface storage coefficients determined by type of tillage
18	AGNPS	SD	A,D,E,G	CN	n.a.	tillage influences C factor as in RUSLE
19	Jak/Dex	ML	A,C	Kmax	SR	soil density and strength
20	LEACHMN	ML	A,C,F	Rich, simple	Rich	through management information
21	NTRM	ML	A,D,F,G,H	Rich, dyn	Rich	tillage information translated into changes in soil properties
22	SWAP	ML	A,C,F,H,I	Rich, dyn	Rich	indirect
23	SWIM	ML	A,C	Rich	Rich	sealing, crusting, surface roughness
24	WAVE	ML	A,C,F,H,I	Rich	Rich	indirect
25	WAVES	ML	A,C,F,H	Rich	Rich	indirect

nr name	type	functions	surface layer simulation	water movement	tillage and/or other farming components
26 WEPP	ML/D	A,C,D	GA, Rit	SR	all tillage activities, incl. planters, residue incorporation
27 MUTILLS	ML	A,B,C,D	n.a.	Darcy	tillage induced soil aggregation and porosity, structure linked to infiltration
28 DUET	ML	A,B,C,H,I	dyn	SR	through infiltration and weeds*
29 ENWATBAL	ML	C	EB	Darcy	indirect
30 DAISY	ML	A,B,C,G,H,I	Rich, dyn	Rich	system management, incorporation crop residue, manure
31 CP-BKF 3	ML	A,B,C,F,G,H,I,J	n.a.	SR	ploughing and ridging (surface storage)
32 DNDC	ML	A,B,C,D,G	n.a.	n.a.	C and N dynamics: effect of tillage

A = water infiltration / runoff, B = water redistribution, C = evaporation, D = erosion, E = sediment yield, F = solute percolation, G = NP fluxes, H = crop growth, I = crop yield, J = crop residue
CN = Curve Number, Rit = Ritchie, EB = energy balance, Rich = Richards equation, SR = storage routing, n.a. = not applicable (is not explicitly used in the model), dyn = dynamic * = cf. case 5

Literature:

1 Renard et al (1991)
2 Elwell, 1978
3 Rose et al, 1983
4 McCown et al. (1996)
5 Knisel (1980)
6 Stockle and Donatelli (1996)
7 Williams et al. (1990)
8 Leonard et al. (1987)
9 Littleboy et al. (1989)
10 Saxton (1984)
11 Hess (1994)
12 USDA (1990)
13 Affholder (1997)
14 Franquin and Forest (1977)
15 Arnold et al. (1994)
16 Williams et al. (1985)
17 Beasley et al. (1980)
18 Young et al. (1989)
19 Jakobsen and Dexter (1987)
20 Wagenet and Hutson (1989)
21 Shaffer (1985)
22 Kabat and Feddes (1995)
23 Ross (1990)
24 Vanclooster et al. (1992)
25 Hatton et al. (1995)
26 Lane and Nearing (1989)
27 Porter and McMahon (1990)
28 Huygen (1988)
29 Lascano et al. (1987)
30 Hansen et al (1990)
31 Verberne et al (1995)
32 Li (1995)

Summarizing, the role of tillage in the various models is found or expressed in the following processes:

- creation of surface roughness, influencing surface storage and detention, and setting a friction (resistance) factor for water flowing over that surface (Manning's n),
- mixing and incorporating crop residue, influencing stability of the soil surface and the supply of organic material in the arable layer,
- placement of fertilizer in the arable layer (thereby determining the risk of

removal of the fertilizer by erosion),

- influencing the C factor (crop management) in USLE-type models
- changing soil structure (density, aggregation), influencing the ψ-θ and ψ-K relationships (used in the Darcy and Richard equations for water movement)
- the shattering (and re-formation) of surface seals and crusts, resulting in changes in infiltrability

Detailed examples of the application of a modelling approach of tillage with respect to soil and water conservation are given in cases 5 and 6. In 4.2, the role of tillage in modifying soil structure and the way by which these effects can be modelled, is discussed.

4.2. Tillage: soil and water

4.2.1. Introduction

Water is by far the most important property which is subject to modelling: water is crucial for plant growth, but it is also the most important medium by which nutrients, chemicals and fine soil particles are transported in the soil profile. Models of water movement are characterized by a division (a) of the time in calculation steps, with an update of the values of the variables after each step, (b) of the soil profile in layers ranging in thickness from mm's up to tens of cm's, (c) of the field or watershed with 3-dimensional[14] (*'SD'* or *'MD'*) models in compartments of square metres up to hectares.

The major components of the water balance are:

$dS = P + G + R_{on} - E - T - D - R_{off} + Irr$, with dS = change in water content of soil profile, P = precipitation, G = groundwater inflow, R_{on} = runon, E = evaporation, T = transpiration, D = deep drainage, R_{off} = runoff and Irr = irrigation. This is illustrated in Fig. 34, where a typical one-dimensional situation is depicted: water is moving downwards or upwards, with 'sink' terms such as uptake by roots (mainly for transpiration) and possibly runoff (water is 'removed' from the soil surface). In the one-dimensional situation (in simulation terms, a typical 'point' or 'plot'), three areas may be distinguished: (a) the soil surface (precipitation or irrigation, evaporation, infiltration, runoff); (b) in the profile or the rootzone (movement, (re)distribution), and (c) at the bottom (deep drainage or flow from or to the groundwater). In dryland farming situations like the SAT, processes at the bottom of the simulated profile (G and D) are generally absent, but R_{off} and R_{on} are important.

[14] These models are not truly 3-dimensional: the processes at the surface are 2-dimensional, whereas processes in the soil profile are 1-dimensional only.

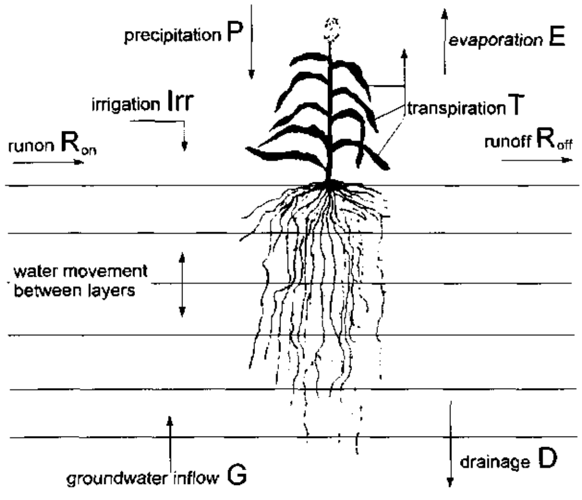

Fig. 34. Graphical presentation of a model.

Many models listed in Table 29 are two or three dimensional: the movement of water in, but particularly at the soil surface in lateral direction is also taken into consideration. The quantity, velocity and routing of the water flowing off is determined, based on soil surface conditions such as slope, slope length and shape, roughness etc. Runoff and runon, characterizing the situation on a field or catchment (watershed) can thus be simulated and quantified.

In above situations, tillage has a strong impact on important model parameters. Tillage alters the soil structure around the soil surface, normally down to a depth of at most 20 - 30 cm. Tillage also influences the fate of dead or live vegetation and other material (e.g. farmyard manure) present at the soil surface.

Changes in soil structure can be quantified in models by changing related parameters such as soil hydraulic characteristics, but also parameters such as stability, mechanical resistance to forces applied by tillage and traffic or rain and wind etc.

An additional complication in modelling tillage is the fact that changes in soil structure induced by tillage are sudden and abrupt (loosening, crumbling, mixing etc.), to be followed by a much slower structure modification under 'natural' processes of wind, water and crop development. So, when these structural changes take place in the period of time simulated by the model, they form a complication in the parametrization of the model.

Because of this, parameters related to structure were usually kept constant in the first generation of simulation models.

4.2.2. Influence of soil structure and the effect of tillage

The most important effects of soil structure as they are represented in models are: (1) the water holding properties, (2) the infiltration of water into the profile (sealing effects), (3) the evaporation of water, (4) the movement of water at the surface (runoff and runon) and (5) the movement of water within the profile (conductivity or permeability). These effects will briefly be treated in terms of their role in the water balance calculations and the possibilities of modelling these.

Water holding capacity

This property is generally expressed by the difference in moisture content (*mc*) at the permanent wilting point and at field capacity. The values of *mc* at various potential levels depend strongly on the texture of the soil, the presence of organic matter, but also on the structure of the soil (aggregation, density). This effect is strongest at pressure head values close to zero (near saturation) and is hardly noticeable at values below FC (where the smallest pores only are still filled with water).

Two major structure characteristics influence the shape of the pF curve: the density and the pore-space distribution. When a soil is tilled with e.g. a plough (chisel, mouldboard), then the main effect is loosening of the soil matrix by the formation of large clods or aggregates, and thus by large voids. The typical effect on the pF curve was given for the sandy 'Labucheri' soil from Niger in Fig. 17. The mc at saturation (θ_{sat}, at ψ=0) will increase. Due to a shift in the distribution of pore sizes (the number of pores with intermediate sizes may have reduced), the pF curve in the range around FC may be lower. The effect is hardly visible beyond suctions of approx. 10 kPa, where only the finest (intra-aggregate) pores play a role. Other tillage operations, e.g. fine harrowing may also increase the θ_{sat}, but less so, and the effect is usually larger in the suction range determined by the intermediate pore sizes. Compaction by rolling, or by traffic will of course decrease θ_{sat}.

An important practical problem is the fact that a loosened layer at the soil surface is normally not very stable. Due to natural consolidation or under the influence of external forces such as rainfall, treading by persons or by animals, and traffic, the pore volume will change again. In Figs. 35a and 35b, upheaval (as an indicator of the increase in pore volume of the tilled layer) after tillage and subsequent consolidation in time, as measured during the experiments in Brazil (case 3) and Niger (case 4) is shown. The effect of traffic is much higher than that of the natural forces such as rainfall. In the mechanised tillage situation in Brazil, the loosening effect was decreased by approx. 50% after secondary tillage and reached 100% after planting.

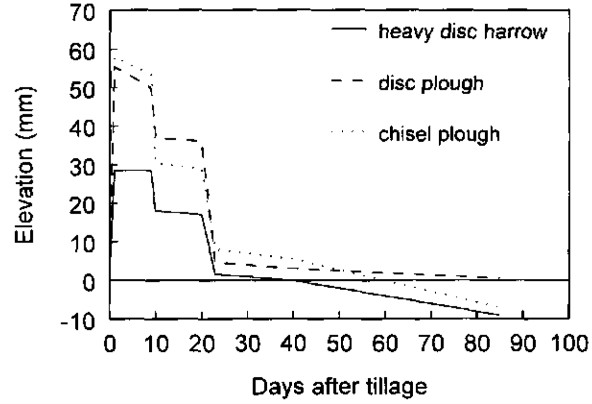

Fig. 35a. *Upheaval and consolidation (case 3).*

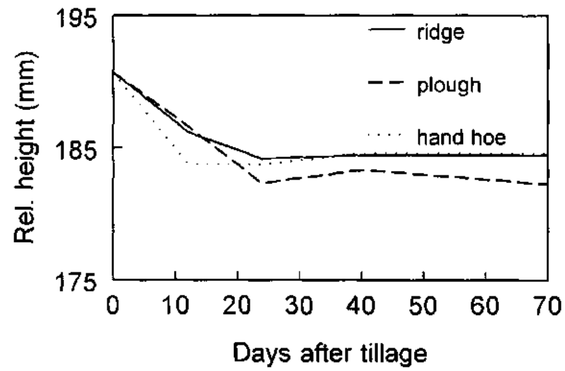

Fig. 35b. *Consolidation after tillage (case 4).*

With functional or 'budget' models, the water holding capacity can be expressed simply in terms of a quantity: a certain amount (mm's) of water which can be stored in a soil profile layer. Sometimes this quantity is tied to one or two critical pF values, such as FC and saturation. Mechanistic models will require a more complete pF curve.

Water infiltrating into the profile

Water in contact with the soil surface may enter into the profile via the pores open to the atmosphere because of soil water potential and gravity forces. In certain situations, the flux of water reaching the surface is higher than the flux of water infiltration, so all water cannot enter instantaneously. A low 'infiltrability' can be caused by: (a) very high moisture contents (saturation or near-saturation) of the upper soil layers, resulting in a small potential gradient, (b) a very low hydraulic conductivity of the soil surface layer. This latter situation is typical for a sealing soil. Seals and crusts may be very quickly saturated under rainfall, but the movement of water through these crusts or seals can be extremely slow. In addition, air may be trapped in the pore system under the seal and thus infiltration is reduced even further.

The direct effect of tillage of a sealed or crusted surface is the disruption of the continuously sealed layer, thus creating clods interspaced with large pores, exposing the underlying, aggregated soil, thereby increasing the roughness of the surface. For water infiltration the effect of breaking up a dense surface layer is twofold: the exposure of large pores allows water to be taken up by the surface layer, but at the same time the 'micro' storage is increased.

For each particular soil type the intensity and mode of tillage is crucial in determining the final effect on infiltration and the behaviour under subsequent rainfall.

On heavy soils, tillage of crusted toplayers will create a rough and open surface (it is practically impossible to work superficially on hard clay soils). Rainfall will not easily form a crust again.

On lighter soils (loams), crusts can be broken by shallow tillage (e.g. weeding), leaving a rather smooth surface. Deeper tillage will create a higher roughness, but in both caes rain will quickly restore the crust and flatten the surface.

Macropores contribute greatly to infiltrability. For cracking clay soils, 95% or more of rain or irrigation water can infiltrate through the cracks (Hoogmoed and Bouma, 1980). A high infiltration through macropores can be achieved only when the pores are open to the surface. Water flow into cracks takes place at zero suction and thus even very superficial tillage may be enough to close off the openings. Dixon and Simanton (1979) distinguish between *roughness* as the microrelief producing depression storage and *openness* as the macroporosity visible at the soil surface.

In most models, rainwater is assumed to enter directly into the surface layer in the absence of restricting layers. When rainfall intensity exceeds the flow rate into deeper layers, then the surface layer may become saturated, a layer of free water will start building up, and runoff may be initiated.

When a crust or seal is present, the calculation of flow through this restricting layer can be done in different ways, Ahuya and Schwartzendruber (1992) and Bristow et al. (1995) present a review of the various approaches:

a. The crust or seal is considered as a separate layer with its specific characteristics (ψ-θ and ψ-K relationships) as mentioned earlier: thin, high density, very low K values. A serious difficulty here is that the thickness of the layer is not accurately known, so a deviation of a few mm's or less may already have a strong effect on the calculated flow.

b. The crust or seal is treated as a thin saturated layer with constant properties as hydraulic resistance or conductivity. These properties may also be changing, e.g. when the seal is formed under rainfall, and can be expressed as a function of time or cumulated rainfall (kinetic energy).

In functional models, the effect of a sealed surface is handled as a boundary condition, with e.g. a maximum permissible flux of water through the soil-air interface. This is also the case with models where the results of infiltration studies using natural or simulated rainfall are used. The formation of the seal/crust is expressed as a diminishing infiltration rate, as a function of cumulative rainfall.
In mechanistic models, the term 'crust resistance' is often used when more soil physical information is available. Resistance r is the thickness of the crust L_c divided by K_{sat}, the saturated hydraulic conductivity of that crust: $r = L_c/K_{sat}$ (Ahuya and Schwartzendruber, 1992). The Green-Ampt approach for calculating infiltration is also used frequently. In this method, the 'effective hydraulic conductivity K' can be adjusted according to the presence or build-up of a seal. Since the calculation of the infiltration rate with Green-Ampt requires knowledge of the distance to the wetting front, assumptions of the speed of advancement of the wetting front have to be made.

Evaporation
Evaporation of water into the atmosphere is also negatively influenced by restricting layers. The low K value of the crust will reduce upward flow of water as well. Breaking up the crust by tillage will create a much larger surface exposed to the evaporative forces and thus the tilled layer will dry quickly. On the other hand, the evaporation front moves downward due to the disruption of the small pores and in the longer term the effect of tillage is opposite to what was achieved immediately after the operation.

For modelling evaporation, the factor heat is very important. Mechanistic models, therefore, will take into account this major factor determining the evaporative flux. This requires knowledge of the energy balance at the soil surface. Both mass and energy flows have to be determined. Calculations of the evaporation rate E can be based on net radiation and heat fluxes through soil and air, or can be related to air humidity, temperature and windspeed. Both mass and energy flow have to be calculated to describe evaporation.
In the functional models, evaporation can be modelled by calculating or assuming an evaporative demand, based on simplifications of the calculation as done in mechanistic models (Stroosnijder, 1987). Typically, the actual evaporation from the surface layer of the soil profile is a fraction of the potential evaporation, with this fraction being a function of the moisture content of the surface layer. Evaporation is usually assumed to take place in two stages: the constant rate stage (K in the surface layer(s) is high enough to

satisfy the evaporative demand) and the falling rate stage (where the hydraulic properties of the soil become limiting).

Resistance to overland flow (runoff)
At the soil surface, three factors determine the fate of water that cannot infiltrate into the profile: 1. the slope, 2. the hydraulic resistance against flow and 3. the surface storage.
The most important soil and related variables that influence these factors are: (a) random roughness, (b) roughness in a specific direction (or ridge height), (c) soil strength or stability and (d) amount and condition of living vegetation or plant residues.
(a) Random roughness. Any tillage activity or other soil manipulating action will create roughness. When no specific orientation of the surface shape is created, the result may be called random roughness. (b) When the soil is arranged in a regular pattern, there is a marked difference between roughness measured in the direction of tillage, and measured perpendicular to it (Table 30). On sloping lands this will have a strong effect on storage and movement of water. (c) Soil strength influences the rate of flattening of the surface (reduction of roughness) and the rate of crust and seal formation. (d) Crop residue generally increases the strength of the surface layer, thus improving the resistance to external forces, and residue parts (stems, leaves) act as a physical barrier to water flowing overland.

Table 30. *Influence of direction of tillage on roughness of the sandy Labucheri soil (case 4), expressed as roughness in mm.*

	ridge		plough		hand hoed	
	↔	↕	↔	↕	↔	↕
after tillage	70.1	15.2	46.8	12.0	38.6	9.4
70 days later	63.7	12.2	46.6	9.8	36.4	7.2

↕ direction of travel, ↔ perpendicular to direction of travel
roughness: standard deviation around average level

A quantification of the roughness created by tillage (both random and directional) can be achieved by assigning characteristics for each type or group of implements, possibly corrected for working depth and soil type or condition (tillage of a dry, hard clay soil will result in a higher roughness than moist, light soil). A smoothening of the surface (roughness decay) will start when rainfall hits the tilled surface. Some form of exponential decrease of roughness with cumulative rainfall as a driving variable may be applied. The decrease will be slowed down when the strength of the soil surface is reinforced, e.g. with residue or because of a high clay content.
Roughness at a certain slope determines surface storage and resistance to

Roughness at a certain slope determines surface storage and resistance to overland flow. There is, however, no clear relationship between these variables, although in hydrology roughness factors can be used for water flowing over a surface (Manning's *n*).
In case of a directional roughness, so when the exact shape and direction relative to the slope of is known (e.g. under ridges or plough furrows), then depressional surface storage may be calculated. Surface storage cannot be calculated from random roughness because it is very difficult to quantify the connections between depressions (though in some models assumptions are made).
As indicated above, the rate by which roughness decreases depends strongly on soil (aggregate or clod) stability and the presence and condition of residue. Stability of the soil is a function of texture and organic matter. The way and amount of crop residue incorporated in the top layer of the soil by tillage depends on the type of implement, soil and residue type, and the moisture conditions during tillage. As for the creation of roughness, implement characteristics are available to predict the tillage effect.

Table 31. *Characteristics of some implements with respect to the creation of surface roughness and the incorporation of crop residue.*

implement	Rr (cm)	frT	Rh (cm)	width (cm)	depth (cm)	frBf %	frBn %
Chisel plough (coulters,straight spike points	2.3	1	5	30	15	65	40
Chisel plough (sweeps)	2.3	1	5	30	15	45	25
Disk plough	3.8	1	5	20	10	90	85
Disk harrow (single gang)	2.6	1	5	20	5	50	40
Field cultivator (duckfoot points)	1.5	1	2.5	30	5	60	45
Furrow diker (ridge tier)	1.5	0.7	2.5	75	5	20	10
Spike tooth harrow	1.5	1	2.5	5	2.5	30	20
Mouldboard plough	4.3	1	5	40	15	98	95
Paraplow	1	0.3	2.5	36	20	20	15
Rodweeder (rod only)	1	1	2.5	13	5	40	10
No-till planter, ripple coulter	1.2	0.15	2.5	75	0	15	10
Mouldboard plough (animal traction)*	4.3	1	5	25	10	85	80
Handweeding*	0.8	1	1.5	20	3	5	5
Handhoeing*	1.1	1	2.5	15	5	15	15

* estimations based on own research

Rr = random roughness, frT = fraction of surface tilled, Rh = height or ridges created, width = distance between working parts of implement, depth = effective working depth, frBf, frBn = fraction buried (fragile, resp. non-fragile residue).
Source: Stott et al. (1995), Alberts et al. (1995).

In Table 31, a listing is given of the assumed effect of a number of typical tillage implements used in dryland farming. Conventional implements such as the disc and mouldboard plough bury a large fraction of the above-ground crop residue (between 85 and almost 100%), whereas typical conservation tillage tools (chisel ploughs) leave much more residue at the surface. Long-stemmed and thick crop residue as from maize and sorghum is more difficult to bury ('non-fragile') than finer broad-leaved material e.g. from groundnut and soybean ('fragile'). The roughness data should be considered as approximations only: the resulting surface configuration also depends strongly on the soil type and condition. The roughness figures given in Table 31 are comparable to those found in case 3 (Table 24). This type of information is crucial in models addressing surface structure, but also in those using energy requirements and workability (timeliness).

In one-dimensional models free water at the soil surface is considered runoff (usually when this layer exceeds a certain level) and is treated as a 'sink' term. The rate by which water runs off can be made a function of various surface characteristics such as roughness, slope etc. If the location of the simulated plot or point is considered to be a depression, runon water can be presented at the surface as a 'source' term.

In functional 3D models, sometimes a 'runoff-resistance' parameter is applied, based on slope and surface roughness, but in the large majority of these models the 'curve number' (CN) function is used. This function, developed by the USDA Soil Conservation Service (USDA, 1972) applies a series (100) of numbered curves depicting the relationship between rainfall depth and runoff. Curve number 0 implies no runoff at all, curve number 100 means all rainfall runs off. The relationship between rainfall and runoff is not linear and curves do not start at rainfall = 0. The method is developed for calculation of runoff from watersheds and choice of a curve is based (a.o.) on (1) a division of soils into 'hydrological soil groups', based on their infiltration capacity in a wet condition, (2) a distinction between three 'antecedent moisture conditions', (3) different types of land use or cover and 'treatment or practice in relation to hydrologic condition'. The latter factor is influenced by the tillage system. In the original method, there was a distinction only between fallow, row crops and small grains, with a subdivision in straight rows and contours. Rawls and Richardson (1983) have extended this list with the effects of conservation tillage, which is the result of soil manipulation by tillage plus protection by a crop residue mulch. Rainfall simulator experiments can also help establishing more reliable curve numbers to quantify the effect of soil management (Littleboy et al., 1996). The nature of the approach does not allow calculation of dynamic crusting and sealing processes as will occur after tillage. The size of the watershed is not a factor in the determination of CN, but a weighted average of CN's applying for different parts of the watershed can be used.

In three dimensional mechanistic models various aspects of runoff are calculated in much more detail, using spatial information. Concentration of runoff flow into rills and channels, down to the outlet of the catchment is quantified.

Scale In most models, the movement of water in the soil profile and the growth of the crop is represented at a point. Part of the water balance in these 'point' models is excess water at the surface. The fate of this excess water is ponding water or runoff, possibly creating erosion. In many models the plot or field is assumed to be uniform in characteristics. In the cases presented here, the same approach has been followed. Still, for larger catchments, this is not adequate. Differences in soil type, slope, soil depth, crops grown, management etc. may cause a redistribution (concentration in rills or gullies, infiltration in depressions or flat areas) of runoff water and related phenomena. Repeated applications of the model for different fields can serve as a solution of the problem of the spatial component. Functional models are easier to use in this respect than mechanistic models since the parameters of functional models are generally optimised for larger (watershed or field) scales. The combination of mechanistic models with GIS also seems to be a promising approach.
For mechanised soil tillage, where the weight of the tractor may cause compaction under the wheel tracks, resulting in zones with lower infiltration and poorer root growth, field-averaged input data are not useful if e.g. erosion risk is to be assessed. In the agricultural region in Paraná, Brasil as described in case 3, erosion frequently was found to be initiated in wheel tracks, even when they were invisible at the surface after seedbed preparation.

Water moving through the soil profile
Water moves in the soil profile due to forces caused by gravity and differences in water pressure potential. The hydraulic conductivity is a function of soil water potential: $K(\psi)$. There is a strong effect of both texture and structure on the shape of the K - ψ curve.
The effect of structure on K - ψ is less clear than on θ-ψ (shape of the water-filled pores (bottlenecks), and their continuity). A loosening of the soil will lead to a very strong increase in K at ψ values near zero, but in a decrease at low potential values (in dry soil with very few water-filled pores). The effect on K_{sat} for the Labucheri soil (cases 2 and 4) was given in Fig. 18.
The effect of wide pores created by tillage can be extremely high. The high conductivity, however, is effective only when the large pores are continuous. Tillage induced macropores (typically created by ploughing or chiselling) may collapse due to consolidation and traffic, or subsequent tillage operations like harrowing. Tillage also easily disturbs the continuity of the natural pores, revoking the positive effect on water transport.

In functional models, water movement between layers within the soil profile

usually is based on a simplification of the physical laws: water moves between layers depending on the difference in water content of each layer ('budget' or 'storage routing'). Other empirical models use methods such as 'tipping bucket' or 'cascades', with defined (fixed) hydraulic conductivity and water holding capacities of each layer.
In mechanistic models water flow is calculated using one or other form of Darcy's law (Richards equation), with the matric potential difference between adjacent layers as the driving force, and the conductivity (the $K(\psi)$ relationship) as the governing flow resistance. $K(\psi)$ may be derived from field or laboratory measurements, or represented as a function of texture and structure (pedo-transfer functions, Wösten, 1996).
A combination of ψ-θ and ψ-K relationships, together with the appropriate boundary conditions, allows the 'physically correct' calculation of water flow between layers. This, however, holds true for soils without macropores. Flow in such pores (worm channels, cracks) requires a different approach (Booltink, 1994; Hoogmoed and Bouma, 1980).

4.2.3. Measurement of soil structural variables modified by tillage

A treatment of the methodology for the assessment of all parameters needed in models is beyond the scope of this thesis. For a comprehensive treatment of the available methodology, reference is made e.g. to Klute (1986) and Smith and Mullins (1991). Clearly, there is no sense in attempting to model effects of soil structural changes if the required parameters cannot be measured. The type or class of simulation model will prescribe the choice of parameters to be measured and their degree of accuracy or reliability. In the following paragraphs, only the assessment of those parameters of importance to soil and water conservation, as influenced by tillage and to be used in models, will be discussed.
The main difficulties in measuring tillage-induced structural changes are: (a) the fact that most forms of tillage have a loosening effect on the soil, thus causing the soil matrix to be rather unstable. This makes sampling without disturbing the 'fresh' structure very difficult and often even impossible, (b) the measurements are always time-dependent.

Bulk density
Apart from the standard core samples, density of tilled soil can also be measured using radiation (gamma-probes) or FD (frequency domain; Perdok et al, 1996). The change in bulk density by tillage operations can also be assessed by measuring the upheaval of the soil surface due to tillage, as was done to obtain Figs. 30 and 35, using a reliefmeter.

The ψ-θ relationship
The commonly used method of applying a known suction to an undisturbed

soil sample using a sand bin or pressure plate equipment will yield accurate data when the soil density is not changed during the process. This makes the method not well suited for very loose soils, particularly when measurements are made along a drying curve, which requires a near-to-saturation situation at the start of the measurement. The relationship between suction and moisture content can also be assessed by simultaneous measurements of both variables *in situ* (using tensiometers and non-destructive methods for measurement of mc, such as neutron probes or TDR). Tensiometers cannot be used in loosened topsoil, because contact of soil with the ceramic cup is poor and this layer dries out quickly below the air-entry value of the cup.

Hydraulic conductivity
A detailed review of methods for determining this parameter is given by Klute (1986) and Dirksen (1991). The typical restrictions that apply for tilled soils are: the layered nature, the instability of the tilled layer, the presence of macropores in the tilled layer. For the tilled and crusted layers, a few methods such as the crust method and tension infiltrometers can be used because they do not seriously disturb the structure. In many cases, K values are predicted using pedo-transfer functions (Wösten et al., 1995).

Aggregate stability
An important way of assessing and quantifying the effect of tillage is to measure the stability of the surface layer by wet-sieving methods. The results of this rather simple test shows a good relationship with resistance to natural erosive forces (Terzaghi, 1996). Aggregate stability is also an indicator of the rate of seal and crust formation under rainfall.

Infiltration
Two systems are used to measure infiltration of tilled soils:
a. Water is applied to the soil surface without any kinetic energy (ponding, flooding). This simple system (double ring) is not well suited for crusting soils because on the one hand the existing crust may be damaged by inserting the steel rings, and on the other hand, the water applied has no energy to form a seal. Also, the layer of water which has to be applied will cause a collapse of the large pores in freshly tilled soil.
b. Water is applied as falling drops (rain). The use of artificial rain with sprinkler infiltrometers of rainfall simulators is a much more realistic method to determine the intake rate or infiltrability of the soil surface. This method yields a quantitative and dynamic picture of the process of sealing and crusting under rainfall. One single curve representing the change in infiltration rate as a function of time or cumulative rainfall can effectively be used in calculations or simulation models. The use of simulators was treated in detail in case 1.

Surface shapes and roughness
The reliefmeter or surface roughness meter is the most appropriate instrument to measure the effect of tillage and working depth. It can be done with very simple methods (case 3) or with sophisticated methods (laser-beams).

4.3. Tillage: agronomic factors

4.3.1. Tillage and crop growth and development

Nearly all models mentioned in Table 29 have a crop growth module. The influence of tillage on growth-governing processes is primarily through the soil water balance with its nutrient movement linked to it. Apart from that, there are some direct effects as well:
(1) Tillage has an effect on modifying the soil structure where high density causes a mechanical barrier for root development (hardsetting soils, hardpans or ploughsoles) or emergence of seedlings (crusts). Mechanical breaking of disturbing layers may be needed to prevent crop failure.
(2) The sowing date depends on the opportunities for seedbed preparation: in case of hard, dry soils (or soils which are too wet) tillage may have to be postponed or can be done with heavy equipment only.
(3) An important agronomic effect of tillage is the influence on competition between crops and weeds for water, nutrients and light through mechanical weed control. This effect is included in the DUET model which is discussed in case 5. Currently, there are very few attempts to mathematically model more complex situations as typical in integrated pest management, where tillage may play a crucial role (Doyle, 1997).

4.3.2. Tillage and the nutrient balance

The effect of tillage on the nutrient balance in non-irrigated farming lies outside the scope of this thesis and will not be treated in detail here. However, important factors in this respect are:
(g) movement of nutrients in the soil profile takes place mainly in soluble form with the water. So the effect of tillage on the water balance is also applicable to the nutrients
(h) in situations with low external inputs, the nutrient supply from sources other than fertilizer is very important. This supply is in the form of green manure, farmyard manure and crop residue. The tillage method determines how and where this material is placed in the soil. The mineralization or decomposition of organic matter is a crucial factor. Because of its influence on the placement, tillage (for given climatological conditions) has a strong effect on the rate of decomposition. In the next

chapter, this aspect will be given more attention.

(i) tillage has an effect on the proliferation and distribution of roots. In doing so, there is an indirect effect on the possibilities for nutrient uptake by the plant.

(j) tillage as a technical measure controls the (precision) placement of fertilizers

In simulation models, the effect of tillage on movement of nutrients is, as mentioned under (a), always tied to the movement of water. Many models with a crop growth component do not take into account the relationship between rooting depth and nutrient availability, though this may be crucial in SAT situations where rooting is governed by the depth of the wetting front through the rainy season.

4.3.3. Tillage and organic matter

The important function of soil organic matter (SOM) in crop production and soil and water conservation was discussed in 2.1. In this chapter, a brief review of the tillage components of models simulating the accumulation or decomposition of SOM, with particular reference to applications in non-temperate zones, is given.

The cycle of carbon, the most important (approx. 50%) component of organic matter from CO_2 in the atmosphere, through organic compounds in plants, to SOM and back to atmospheric CO_2 is a complex one. Apart from the C-cycle, the fate of N (C:N ratios within SOM may range from >100 to around 4) is not negligible, particularly in low nutrient input systems.

In most models, there is an input from crop residue (both below and above-ground), green manures and weeds, and animal, household and agroindustrial waste. Once in or above the soil profile, processes of decay and mineralisation will start. Various forms of SOM may be distinguished, generally called 'pools' and classified depending on composition, form, size or age of organic material, stability, etc. Each of these pools may have a different rate of decay. During the decay processes, a transformation of C and N takes place. The rate of decay is considered as a function of temperature, humidity and aeration of the environment and the activity of soil biota. Interactions with other minerals may also be included (e.g. the CENTURY model; Metherell et al, 1993).

With climate and soil as boundary conditions, tillage will have a strong effect on the SOM dynamics: a direct one through the manipulation of the inputs (changing the size of the organic material, distribution, incorporation etc.), and an indirect one through the effect on soil structure, which in turn influences humidity, temperature, aeration and biological activity.

A large number of models has been developed recently, with the simulation of SOM dynamics as a primary objective: RothC, CANDY, CENTURY, SOMM, ITE, NCSOIL etc. (see e.g. Smith et al.,1997 and an Internet register[15]). In none of these models, tillage is explicitly used, although the moments of tillage activity are used as inputs to indicate a change in the soil structural conditions, which in turn affects SOM dynamics. Tillage effects on crop residue are treated explicitly in models such as WEPP, where the intensity of damaging the crop residue (cutting in smaller parts) and the degree of burial is a function of tillage implement and residue condition. For the parts buried in the soil, the rate of decay or decomposition then is modelled along the same lines as mentioned above.

4.4. Tillage and time/energy

Although time and energy aspects are not directly related to soil and water conservation, they do form crucial boundary conditions, restricting or allowing use of certain implements or chains of implements as described in 3.

Soil tillage modifies the structure of the soil (4.2). Tillage action (see Table 1) is basically the exertion of pressures (forces causing stress) on the soil matrix. Laws typical in structural and foundation engineering cannot simply be applied in tillage because firstly, loads due to tillage and agricultural machines and equipment are lower, and lasting for very brief periods of time, compared to those of e.g. buildings or dams, and secondly, 'agricultural' soils are relatively loose, whereas soil for foundations often is a dense, massive-structured, material.
The way tillage forces are applied (energy, speed, shape and size of tool-soil contact area) depends on the type of tool and the mode of application. These processes rarely last more than one or two seconds and may be so brief that they can be defined as an impact. The reaction of the soil to pressure is a function of the characteristics of the force application and the condition of the soil (moisture content, density, aggregation) at the moment of tillage. The following types of basic reactions can be distinguished: (1) crumbling and loosening, (2) cutting, (3) compaction, (4) transport and (5) destruction of (micro) structure

A commonly accepted way of expressing the condition of soil in relation to the expected reaction to tillage is by describing and quantifying *consistency.* The relationship between moisture content and mechanical behaviour of soil is shown in Fig. 36.

The soil characteristic '*workability*' is used to indicate the suitability at a certain

[15] SOMNET: yacorba.res.bbsrc.ac.uk/cgi-bin/somnet-models

moment for tillage. A workable condition is found when (a) the desired soil condition can be produced without damage to the structure and (b) this can be done with the lowest or at least acceptable energy use. The optimum workability range is expressed in moisture content or matric pressure.
Workability for a certain soil type is good when this range is wide but when it is narrow or commences at a level where the moisture content is much lower than FC, workability for such a soil is poor because tillage cannot start until the soil has dried for a considerable period after rain.

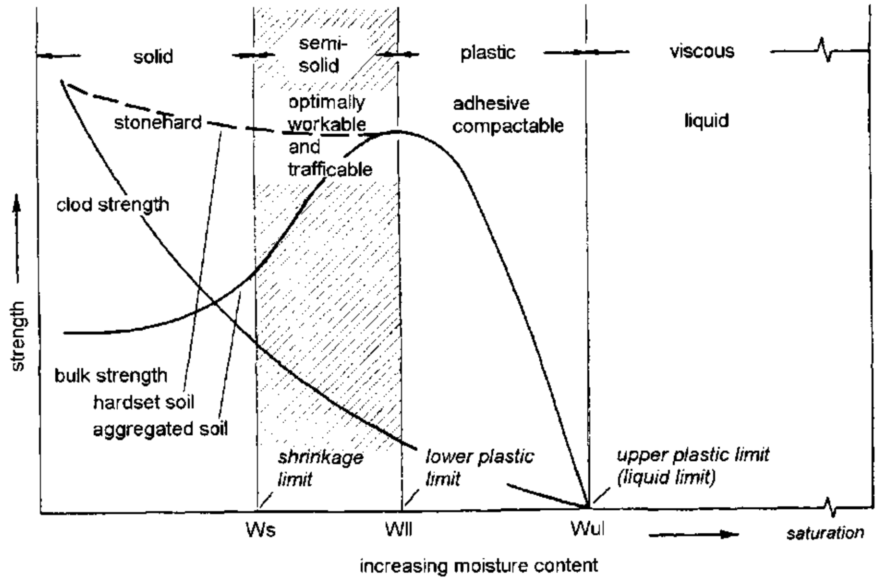

Fig. 36. *Consistency limits and workability as a function of moisture content. The values Ws, Wll and Wul on the X-axis are: water content at shrinkage, lower plastic and upper plastic limit, respectively.*

In practice, workability is not the only factor determining whether the soil can be tilled or not. In addition, the soil profile should be strong enough to carry the weight of a tractor (or animal) and machine ('trafficability'), and traction forces from tractor or draught animal should effectively be transferred to the soil ('tractability'). When drying conditions are strong, the topsoil may be dry enough for seedbed preparation but the subsoil may still be too wet and unable to bear traffic. A very slippery surface, or a very loose and dry surface may cause traction problems. The optimum ranges depend on the type of tillage and the machinery used. For ploughing, for example, the soil will have a much wider workability range than for seedbed preparation.

The workable range of hardsetting soils is narrower than the range of 'normal' soils, in particular for light (sandy, loamy) soils. The main reason is that the workability when expressed as energy requirement, which is the governing factor in the dry part of the moisture range, is cut off quite abruptly. In the moist or wet part of the range, where structural damage is the criterion, the pattern is not different from other soils, as is sketched in Fig. 37.

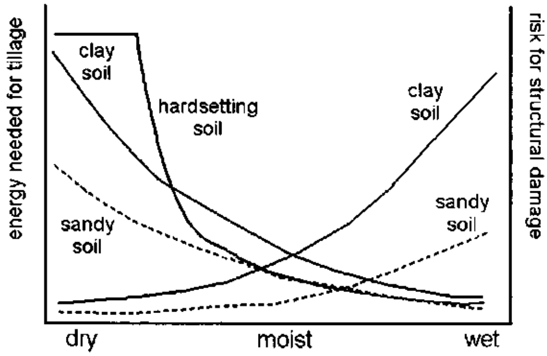

Fig. 37. *Typical workability ranges.*

The following processes may be approached by models:
(a) prediction of soil mechanical behaviour during tillage
(b) energy requirement for tillage at specified soil conditions
(c) time or period that tillage is possible

(a) Only few models are known: Gupta and Larson (1982) discuss two models: soil breakup and soil compaction. For soil breakup, the energy required to create different aggregate size distributions depends on water content, soil, and tillage implement. However, no mechanistic or deterministic model for soil breakup is available. Empirically, it is possible to estimate energy to create a desired aggregate size distribution, and to indicate which type of tillage implement may be able to produce such a soil reaction.
For soil compaction, changes in soil porosity (influenced by applied mechanical stress and water content of the soil) can rather accurately be modelled, even with mechanistic models.

(b) Models have been developed where the characteristics of soil at various levels of moisture content and density are used to calculate energy requirements for specific (tillage) operations. Many of these models are designed for predictions of draught requirement of ploughing with mouldboards or chisels, where tool-specific parameters are based on experiments with downscaled tools (Eradat Oskoui and Witney, 1982; Wismer

and Luth, 1972; Godwin and Spoor, 1977; Gupta et al., 1989). The application, however, of these models is limited to situations where the soil reaction is cutting or controlled failure. Canarache (1993) proposes a model where draught requirements are predicted based on texture, density and moisture content, Eradat Oskoui and Witney (1982) use data from penetrometer measurements (cone-index) as input.
For typical hardset and crusted soils, where tillage generally implies the (uncontrolled) breaking up of the soil matrix, force or energy requirement predictions are very difficult to make. The total energy requirement depends strongly on the final result of the tillage operations, i.e. the degree of pulverisation and the efficiency of the implement used (Wolf and Luth, 1979).

(c) For the assessment of equipment needs and estimations of the time required for certain soil-related operations such as tillage and harvesting, workable periods are determined as ranges of soil moisture content or matric potential in the upper soil layers. Workable periods can then be calculated using water balance models (Goense, 1987; Van Lanen et al., 1987; Droogers et al., 1996; Terzaghi, 1996).

4.5. Application of models

The value of models in agricultural research nowadays is commonly recognized. In spite of difficulties in development of these models for tillage, soil and water conservation and related fields, efforts as to be discussed in the next cases have proven to be relevant. Important areas of research where a meaningful application can be expected are:

- situations with limited access to or availability of data, particularly the data containing information on soils and land use
- situations with a climate which is highly variable, with extremes occurring with intervals of more than 5-10 years
- situations where current field research is limited and where the setup and management of field experiments is costly and time consuming
- situations where development paths have not clearly been identified and thus where scenarios are very useful

In terms of application, mechanisitic models are being used to simulate soil water dynamics, including rainwater infiltration, solute transport and water management, e.g. in irrigation situations. There are also some applications in the effects of fertility and erosion on productivity. On scales larger than the plot, mechanistic models have not been used much.
Functional models are being applied more widely in order to assess interactions between climate and crop management, relationships between erosion and productivity, water quality etc. This use is typically intended for a

larger scale: from watersheds up to countries (e.g. WEPP). The availability of databases with relevant information of the sites for which the simulations are to be run, is crucial.

Representative sites with different soils, slope, and climate characteristics are thus evaluated for different land use or management scenarios in repetitive simulation runs.

The need for very specific parameters is generally the reason why only functional models are used on larger scales. The degree of detail for mechanistic models becomes a restrictive factor. The problem of upscaling from parameters valid for points or very small plots (assuming uniformity) to larger and thus more variable fields or watersheds is big.

Models for farmers' management decision support, where workability, timeliness and soil and water conservation aspects are important factors, are under development, e.g. WEPP (Lane and Nearing, 1989) and GPFARM (GPSR, 1998).

4.6. Case 5. Soil tillage options for water management under erratic-rainfall conditions

4.6.1. Introduction

In the semi-arid tropics, with highly erratic and aggressive rainfall, crop production is influenced by water availability as well as by nutrient availability.
Water availability can be increased by tillage aimed at an increase of the fraction of the rainfall that infiltrates into the soil and the subsequent reduction of the loss of water due to runoff (cf. case 1). The same type of tillage reduces soil evaporation and transpiration losses by weeds.
Nutrient availability can be increased by applying fertilizers, farmyard manure or by the use of crop residues, and by removing competitors like weeds.
Given the severe food crisis in the semi-arid tropics, the development of improved farm practices aimed at an increase of crop production is a major aim of agricultural research. However, socio-economic constraints of the existing farming systems in the semi-arid tropics leave little room for a major increase of inputs of labour or capital in the form of nutrients. Therefore, it is of crucial importance to understand the interrelations between water and nutrient availability in order to optimize the effectiveness of such an increase of inputs.
If e.g. under certain farming conditions (i.e. climate, soil and crop), water is the most limiting production factor it seems logical to aim at water conservation tillage. It has to be kept in mind, however, that improved water availability may lead to increased vegetative growth early in the season (higher susceptibility to drought), to increased erosion risk due to more tillage operations. Also, nutrients may easily become the limiting factor for plant growth when water availability is improved. If indeed under the same farming conditions nutrient availability is considered as the most limiting production factor, one will start looking into possibilities to increase the level of nutrient input. Similar side-effects as referred to above may occur if the interrelations between water and nutrient availability are not well understood or not taken into account properly.
An improved understanding of the subject may lead to the conclusion that water conservation will only be effective with a simultaneous moderate increase of nutrient input. This insight may improve quantitative land evaluation (van Keulen et al., 1987; van Keulen and Breman, 1990; van Diepen et al., 1991) and lead to the design of an achievable package of improved farming practices (Stroosnijder and van Rheenen, 1991).
Simulation offers a tool to provide the required insight into the above stated interrelations not only for development options in arable agriculture (van Diepen et al., 1989) but also in silvo-pastoral zones (Stroosnijder and Hoogmoed, 1991).
In this case study, the use of simulation models to quantify effects of adaptive soil management practices on water conservation and on crop production, is

discussed. This study was preceded by a study dealing with simulation modelling as a means to understand the processes and interactions influencing the crop growth system in the SAT (Stroosnijder et al., 1994). It addressed mainly the effects of water conservation measures. This case concentrates on the combined effect of tillage, i.e. on water conservation (by influencing infiltration and evaporation) and on weed control. The basic assumptions and boundary conditions as given in the first study are repeated here. DUET.91, an integrated public domain research model will briefly be discussed. A case study for millet (*Pennisetum glaucum* (L.) R. Br.) production in the Sahel zone of West Africa will be used to illustrate the possibilities and limitations of this tool.
An improved understanding of the complex phenomenon of crop production with help of a simulation model can direct on-station as well as on-farm research. Results from the model should always be verified with field trials.

4.6.2. The research tool DUET.91

The name DUET was chosen for the simulation model which was used as the research "tool" because elements were combined of existing models (in DUET called modules) developed and documented elsewhere.
Three modules are distinguished in DUET (Huygen, 1988). For crop growth and nutrient requirements, use was made of the WOFOST model (Diepen et al., 1988 and 1989; Berkhout and van Keulen, 1986). The water balance module was based on the SWATRE model (Belmans et al., 1983) and for nutrient availability QUEFTS (Janssen et al., 1990) was used. The model is written in FORTRAN and can be run on a PC.

Module 1:
Crop growth is simulated from emergence to maturity on the basis of physiological processes as determined by the crop's response to environmental conditions. Major processes are CO_2 assimilation, respiration (maintenance), partitioning of assimilates to various plant organs, transpiration and nutrient uptake. Rootable depth grows into the soil at a rate of 4 cm day^{-1}. Actual rooting depth is a function of possibilities for water uptake as determined in Module 2, however there is a maximum, plant dependent, rooting depth.
Nutrient requirement is calculated at crop maturity by multiplying the amounts of dry matter allocated to the various plant organs (i.e. roots, stems, leaves, cobs and grains) with their respective minimum contents of the major nutrients Nitrogen (N), Phosphorus (P) and Potassium (K). These values are known for most crops (van Heemst, 1988).

Module 2:
Available water is simulated at various soil depths (representing soil layers) on

the basis of physical processes like infiltration, redistribution, evaporation and water uptake by the crop's root system. An implicit finite difference scheme is used with 39 soil layers of 7 cm. Water uptake per layer depends on root presence (see Module 1) and available water.

Module 3:

Nutrient availability is calculated using data of the native soil fertility. The latter is represented by the average (0-20 cm top soil) soil's pH (H_2O), organic carbon content, total and readily available phosphorous content and exchangeable potassium. The relationships used to derive the available amounts of nutrients from the above soil chemical data are partly of an empirical nature (crop and soil specific) and partly based on theoretical considerations.

DUET.91 integrates the above modules as follows. In dynamic simulation, using daily time steps, crop production is computed using modules 1 & 2. This results in the so-called water-limited production since neither nutrient uptake nor nutrient availability is taken into account. At maturation the nutrient requirements of this production are calculated using module 1 and compared with the nutrient availability as calculated in module 3. If any of the requirements for N, P or K is larger than their availability, the actual achievable production will be lower than the calculated water-limited production. The actual production is then called a nutrient-limited production and is calculated by dividing the most limiting available nutrient (N, P or K) by the minimum content in the plant organs as defined in Module 1.

A number of features of DUET.91 makes this model suitable for an analysis of the effects of tillage on crop production (in the short-term as well as on the long-term) as a result of its impact on water conservation and weed control.

(1) Crop production and the soil's water balance are interrelated. Management practices influencing this water balance have a direct effect on crop production.
(2) Crop production is dynamically simulated. This implies that an improvement in water availability has an immediate effect on production. This makes it possible to investigate whether an increase in vegetative growth early in the season increases the risk of crop failure later in the season.
(3) Weed competition can be simulated by calculating the influence on radiation interception (LAI) and uptake of water and nutrients, based on plant physiological characteristics.
(4) The soil's infiltration capacity is a function of water conservation tillage and set at a high (empirical) value after tillage. Its value gradually reduces as a function of the cumulative amount of rainfall after tillage. A new tillage operation resets this course of the infiltration capacity.
(5) In Module 1 the crop's potential rooting depth develops gradually as a

function of crop development. In Module 2 it is determined at which depth there is water available for uptake by roots. This availability determines the actual rooting depth. If more than 0.5 mm of water is extracted from a layer during the total growing season, this layer is considered rooted.

(6) Water conservation tillage increases the depth of wetting. Nutrient availability in DUET.91 is made a function of this depth of wetting so that water conservation leads to a more effective mining of nutrients.

(7) DUET can handle various options for the moment that water conservation tillage is simulated. For instance a fixed number of days, e.g. 15, between the tillage operations or a moment related to the cumulative amount of rain, e.g. 100 mm, after the last tillage. The latter may be called response tillage.

4.6.3. The case study

Weather

Average values of maximum and minimum air temperature, relative air humidity, wind speed and irradiation were used since these values show a conservative behaviour over the years as is shown in Fig. 6 (case 1).

Daily rainfall data of 35 years (1950-1984) were used. Since the duration of these storms is not recorded, their intensity is unknown. This implies that these data cannot be matched with detailed information of the soil's decreasing infiltration capacity as e.g. determined in case 1 (Fig.16).

Instead, a separate analysis (Stroosnijder, 1991) was performed to relate size of the daily rainfall to intensity. From a 30-years rainfall record, four normal years with a 50% rainfall probability and four dry years with a 10% rainfall probability were selected. For all years daily rainfall was classified into three classes (<10 mm, 10-20 mm and >20 mm). Within each class, the average rainfall shower was calculated. These averages do not differ significantly between normal and dry years. Within each class, four rainfall intensities, i(1)-i(4), were distinguished, see Table 32. Each intensity is representative for 25% of the amount of rainfall in that class (cf. case 1).

For each of the 12 standard showers defined in Table 32, the duration, t, of the average shower can be calculated.

Table 32. *Average rainfall per class and intensities representative for 25% of rainfall in that class.*

Class	Ave. rainfall in class (mm)	i(1) (mm h^{-1})	i(2) (mm h^{-1})	i(3) (mm h^{-1})	i(4) (mm h^{-1})
< 10 mm	4.4	3	8	18	32
10-20 mm	14.6	5	18	37	61
> 20 mm	32.9	7	34	62	116

Soil

Some characteristic data for a loamy sand at Niono (5° 45' W and 14° 30' N), Mali, were given in Table 5. Additional physical data of this soil (the relationship between moisture content (θ) and suction, and between θ and unsaturated conductivity (K_Θ)) were taken from Stroosnijder (1982). They are presented in Fig. 38.

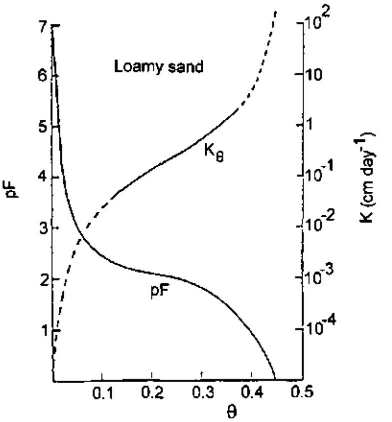

Fig. 38. *Water retention and conductivity of unsaturated soil.*

Based on the distribution of root density (cm cm^{-3}) with depth it may be concluded that in the layer 0-60 cm about 80% of the root density occurs. For each depth X larger than 60 cm, it can be calculated how much root density there is in the layer X-60. By dividing this latter amount by the root density at 60 cm, a relative gain in root density is obtained with respect to the 'standard' density at 60 cm, see Table 33.

Table 33. *Root distribution factor and correction factors for nutrient availability in case roots are deeper or less deep than the reference depth of 60 cm.*

Depth (cm)	Root factor	Carbon factor	Phosphor factor	Potassium factor
0- 20	0.57	0.27	0.14	0.19
20- 40	0.86	0.65	0.52	0.58
40- 60	1.00	1.00	1.00	1.00
60- 80	1.09	1.02	1.04	1.03
80-100	1.14	1.06	1.11	1.09
100-120	1.19	1.11	1.23	1.19
120-140	1.21	1.15	1.34	1.28
140-160	1.23	1.20	1.47	1.38
160-180	1.24	1.24	1.60	1.48
180-200	1.26	1.28	1.76	1.61

Soil chemical data for the top soil as used in QUEFTS were taken as follows:

pH (H_2O)	= 6.0
C	= 2.5 g kg^{-1}
total P	= 100 mg kg^{-1}
P-Olsen	= 4 mg kg^{-1} (= P-Bray, Novozamski, pers.comm)
exchangeable K	= 2 mmol kg^{-1}

A similar procedure was followed for a characteristic distribution with depth of carbon, phosphor and potassium as is shown in Fig.39 (Stroosnijder, 1982; Pieri, 1989 and Stoorvogel and Smaling, 1990. The contents of these elements decrease, increase and remain constant respectively. Multiplying the root factor with nutrient distribution factors yield correction factors for nutrient uptake as shown in Table 33. If roots are at 60 cm depth, nutrient availability is as calculated with QUEFTS in Module 3. If rooting is shallower, availability is less and if roots penetrate the soil into deeper layers the availability increases gradually.

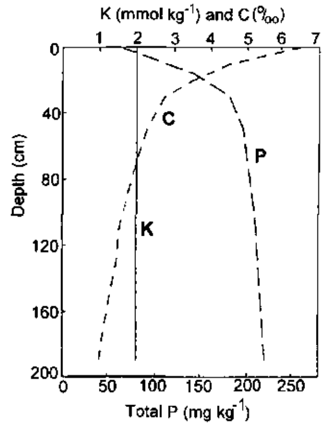

Fig. 39. *Distribution of C, K and P with depth.*

Tillage - water

Cumulative infiltration (CUMI), for each of the 12 standard showers as defined in Table 32 is computed with the equation: CUMI = S $\sqrt{t}$. In this equation, S is an expression for the soil's sorptivity capacity for water. This calculation is performed for three S-values leading to $3 \cdot 12 = 36$ cumulative infiltration values. For each of the above 36 scenarios, runoff can then be calculated with the equation r = P - CUMI - SS. P is the shower size and SS the surface storage, i.e. the amount of precipitation that can be held in the surface irregularities without running off. Three SS values are assumed leading to $36 \cdot 3 = 108$ runoff values.

For crusted, tilled and intermediate soil values for S and SS were taken from data as will be presented in case 6. This leads to runoff values as shown in Table 34.

Table 34. *Runoff percentage for 3 classes of showers and 3 stages of soil surface conditions for a loamy sandy soil in the West African Sahel.*

Class	Average rainfall in class (mm)	Percentage Runoff (%)		
		Crusted	Intermediate	Tilled
< 10 mm	4.4	12	0	0
10-20 mm	14.6	50	14	0
> 20 mm	32.9	74	44	24

Crusted soil: Sorptivity = 1 mm min and surface storage = 0 mm
Intermed. soil: Sorptivity = 2 mm min and surface storage = 2 mm
Tilled soil: Sorptivity = 3 mm min and surface storage = 5 mm

The duration of the effect of tillage is made a function of the cumulative amount of rainfall (CUMRAIN) after the last tillage operation. If this value reaches 100 mm and 200 mm, the intermediate and crusted stages as defined in Table 34 have been reached respectively. DUET.91 interpolates linearly between these points with CUMRAIN as the independent variable.

It is assumed that seedbed preparation tillage and sowing starts after the first rains. Since there is a good chance for viable germination and plant establishment after a decade with more than 20 mm of infiltration, this criterion was used to start the simulation of (crop and weed) growth. This value compensates the seasonable average value for soil evaporation of 2 mm day^{-1} (Stroosnijder and Koné, 1982 and Stroosnijder, 1987). In the simulation runs for the water limited production, the water conservation tillage were supposed to start 30 days before the start of the crop.

Crop

Crop data for Millet (*Pennisetum glaucum* (L.) R. Br.) were taken from van Heemst (1988).

Weeds

Weeds are supposed to have the same physiological characteristics as the crop, which means grassy weeds (*Gramineae*). In principle, development of the weeds was supposed to start slightly ahead of the crop at the (calculated) beginning of crop growth by a 5% higher LAI.

The transpiration and evaporation is modified as a result of the changed radiation interception and shadowing effect due to weed growth. During crop and weed growth total water and nutrient availability is divided over crop and

weeds. Availability of the "immobile" nutrient P is not affected, N availability for the crop is affected with the ratio WFN, calculated as
WFN=WWRAT+(1-WWRAT)*0.5
with WWRAT: water uptake crop / water uptake weeds. Availability of K is supposed to be somewhere between N and P, so here WFN is taken as: WFN=WWRAT+(1-WWRAT)*0.7

Weeding
The tillage operations as used in this model study were supposed to have either a pure weeding effect, so no effect on crusting or infiltration, but purely the elimination of the (competitive) growth of a second "crop", or a combined effect on weed growth and soil hydrological characteristics.

Modelling schedule
In Table 35, it is shown what parameters were used and changed to calculate the effects of tillage and weeding.

Scenarios 1-5 indicate situations where weeds are present; in 1-3, the weeding activity is supposed to be such, that there is also a crust-breaking effect. In scenario 4 and 5, the weeding interval is set at 15 days, with a crust-breaking tillage interval set at 45 and 200 days respectively. Scenarios 6-9 represent situations where no account is taken for weed growth or competition.

Table 35. *Tillage and weeding intervals used in the simulation. The value 0 in scenarios 6-9 indicates a weedfree situation.*

Scenario	Tillage interval (days)	Weeding interval (days)
1	15	15
2	30	30
3	45	45
4	45	15
5	200	15
6	15	0
7	30	0
8	45	0
9	200	0

4.6.4. Results and discussion

The main results of the simulations are summarised in Table 36. These results are averages over the 35-year period 1950-1984, with their standard deviation.

Table 36. Main results of simulation (standard deviations in italics).

Scenario	TI (days)	WI (days)	Rd. (cm)	Runoff (%)	Gryld wl (kg ha^{-1})	Gryld nl (kg ha^{-1})	Actyld (kg ha^{-1})
1	15	15	125	22	829	358	357
			39	*24*	*51*	*34*	*35*
2	30	30	119	26	716	340	336
			39	*20*	*53*	*35*	*36*
3	45	45	114	28	541	317	297
			35	*16*	*56*	*27*	*35*
4	45	15	120	28	733	347	343
			40	*16*	*53*	*38*	*38*
5	200	15	120	31	721	346	341
			40	*14*	*54*	*38*	*38*
6	15	0	140	22	861	394	383
			30	*24*	*49*	*27*	*30*
7	30	0	136	26	810	386	375
			30	*20*	*50*	*26*	*30*
8	45	0	133	28	762	381	367
			31	*16*	*52*	*26*	*31*
9	200	0	132	31	750	380	365
			31	*14*	*53*	*26*	*31*

TI = tillage interval; WI = weeding interval; Rd. = rooting depth; Gryld wl = water limited grain yield; Gryld nl = nutrient limited grain yield; Actyld = actual yield (minimum of water or nutrient limited yield).

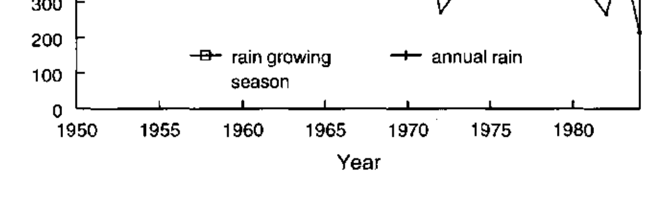

Fig. 40. *Seasonal and annual rainfall over 1950 - 1984.*

Fig. 40 presents total annual rainfall (Average, AVG = 571 mm with a standard deviation, SD = 23%), the rainfall in the period covering the millet growing season of 76 days plus the "tillage governing season" of 30 days

(AVG = 422 mm, SD = 22%). These data show a coefficient of variation of the rainfall of 23% and 22% respectively which is a normal value for SAT climates. Data suggest a trend over 35 years to lesser annual rainfall.
Rainfall in the growing season (76 days) of a short duration millet variety is only 62% and shows a similar decreasing trend.

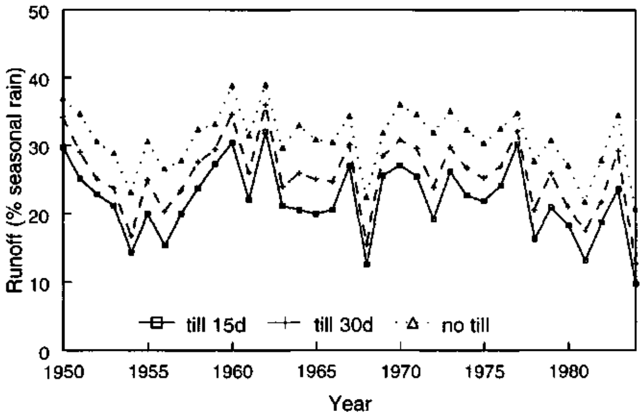

Fig. 41. *Runoff during growing season (% of seasonal rainfall).*

Fig. 41 shows runoff in detail. In this graph, scenarios 1, 2 and 5 (equalling 6, 7 and 9 for this parameter) are represented. Without conservation the runoff during the growing season is as high as 31% (SD = 4%) and decreases with water conservation tillage till 22% while the standard deviation increases till 5%. This reduction of the runoff equals an amount of 37 mm.

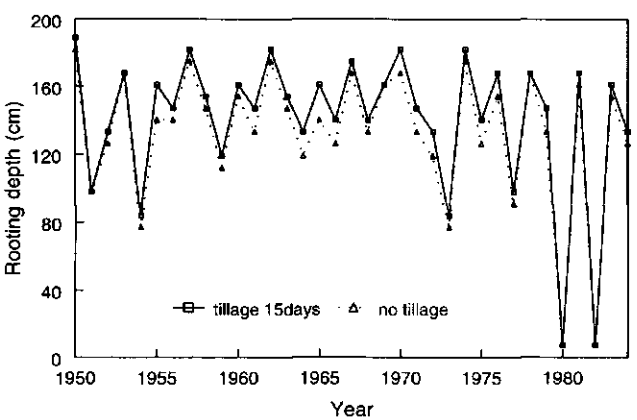

Fig. 42. *Rooting depth (based on wetting of profile).*

Fig. 42 shows the rooting depth of the millet crop as calculated in the water extraction module of the DUET.91 model. Without water conservation tillage and no weeds the average depth is 132 cm (SD = 31%) and with tillage every 15 days this increases only slightly till 140 cm (SD = 30%). In a situation with weed competition, average rooting depth with frequent weeding and water conservation tillage (every 15 days) is 125 cm (SD 39%). A decreasing weeding and tillage frequency to 45 days gives an average depth of 114 cm with an SD of 35%. Since millet can easily root as deep as 200 cm these data show that there is no loss of water due to deep percolation below the root zone.

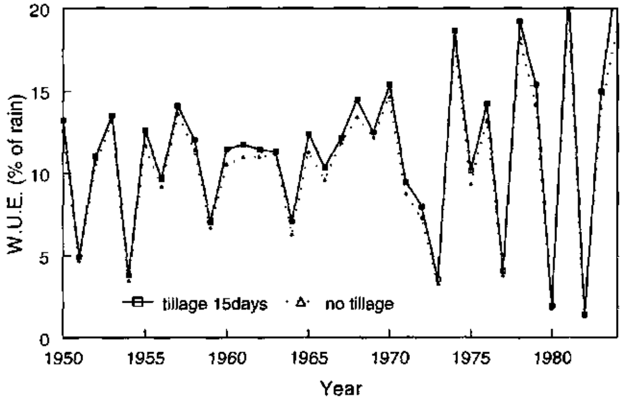

Fig. 43. *Water-use efficiency (transpiration as % of seasonal rain).*

Fig. 43 gives, for the water limited production, the water use efficiency defined as the crop transpiration divided by the rainfall in the growing season. Without water conservation tillage, this efficiency is 10.6% (SD = 43%) and increases only slightly to 11.3% (SD = 49%) if water conservation tillage (15 day interval) is applied. These figures imply that only 45 mm and 48 mm water is used for transpiration respectively. Note that this amount is in the same order or magnitude as the gain in water due to a reduction in runoff from 31 to 22%. Since the total (above ground) biomass is 3067 and 3255 kg dry matter per hectare respectively it can be calculated that the Transpiration Coefficient is 147 kg water per kg dry matter.

Fig. 44 shows the (weedfree) water limited grain production without water conservation tillage (AVG = 750 kg DM ha^{-1}, SD = 53%) and Fig. 45 shows the same data for regular (15 day interval) tillage (AVG = 861 kg DM ha^{-1}, SD = 49%). There is an increase of 111 kg DM ha^{-1} but also an increase in seasonable variation in kg DM ha^{-1}.

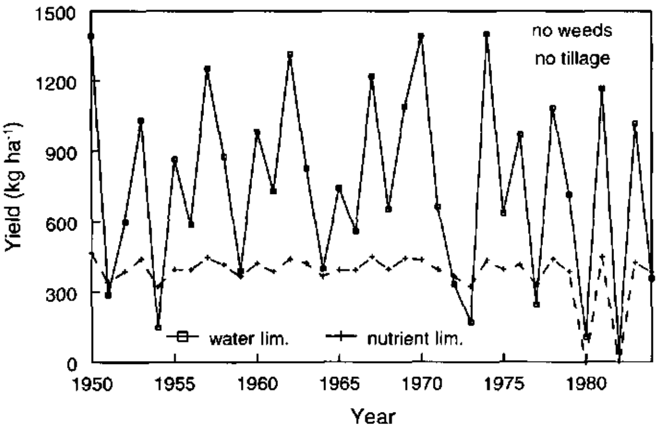

Fig. 44. *Grain production: no-tillage situation (weedfree).*

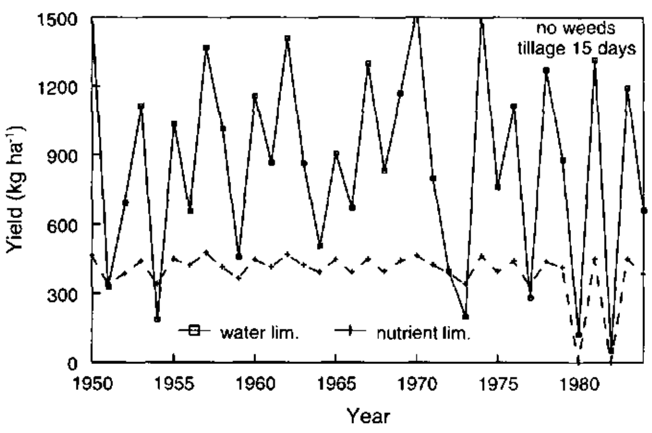

Fig. 45. *Grain production: tillage every 15 days (weedfree).*

Predicted average levels for nutrient limited grain production are 380 kg DM ha^{-1} (SD = 26%) without tillage (Fig. 44) and 394 kg DM ha^{-1} (SD = 27%) with tillage (Fig. 45).

Actual production is the minimum of both calculated levels and is shown in Fig. 46. In 65% of the years this is the nutrient limited production in case no water conservation tillage is applied (Fig. 44). If such tillage is performed every 15 days, this percentage increases till 75% (Fig. 45).

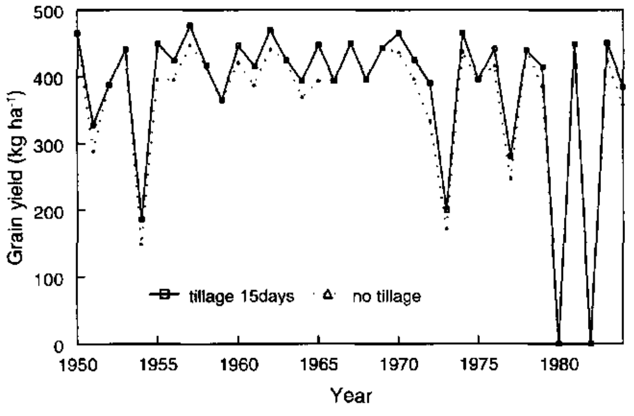

Fig. 46. *Actual (weedfree) grain production (minimum of water or nutrient limited).*

In Figs. 47, 48 and 49 the results with respect to a situation with weed competition is shown. Fig. 47 gives a water limited grain yield of 721 kg DM ha^{-1} (SD = 54%) and a nutrient limited yield of 346 kg DM ha^{-1} with SD = 38%. This applies for a situation without water conservation tillage, but weeding every 15 days.

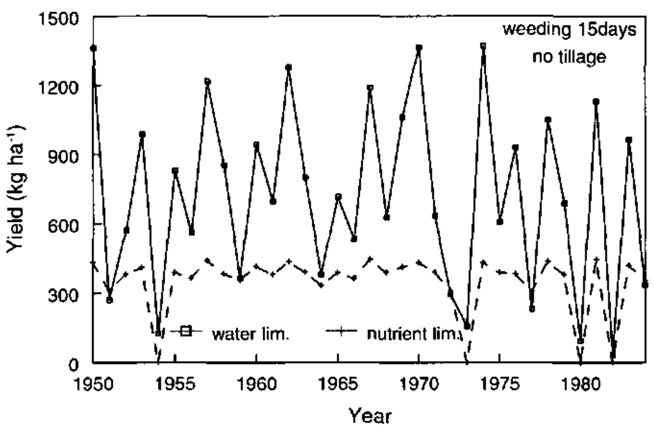

Fig. 47. *Grain production: no tillage, weeding every 15 days.*

Fig. 48 shows the results with both weeding and water conserving tillage every 15 days, Fig. 49 the same, where the interval for the same activities is 45 days. Average yields are 829 (SD 51%) and 541 (SD 56%) kg DM ha^{-1}, respectively. The difference in nutrient limited yields is less: a reduction from

358 (SD 34%) to 317 (SD 27%). The actual production for the weedy situation is given in Fig. 50. Average yields are now 341 (SD 38%), 357 (SD 35%) and 297 (SD 35%), respectively.

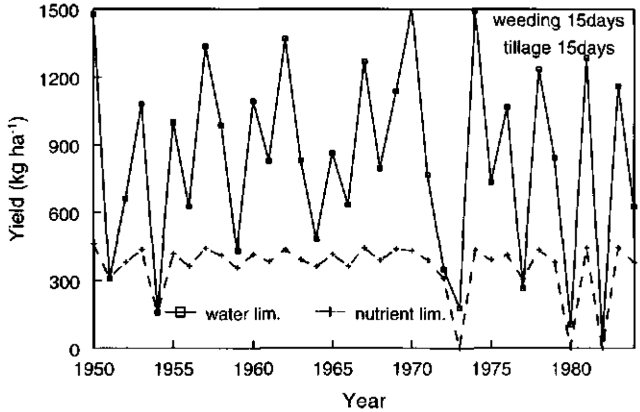

Fig. 48. *Grain production: both tillage and weeding every 15 days.*

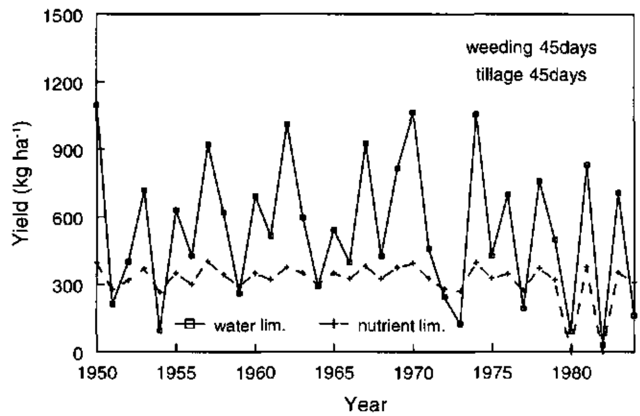

Fig. 49. *Grain production: both tillage and weeding every 45 days.*

The conclusion of this study is that conservation tillage alone (without an additional increase in external nutrient inputs) has a marginal effect. Actual grain production, Fig. 46, increases from 365 kg DM ha^{-1} (SD = 31%) to 383 kg DM ha^{-1} (SD = 30%), i.e. 18 kg only, with no improvement in the production risk. Compared to this, when competition by weeds is considered, there is a clearer effect; weeding plus conservation tillage gave an increase from 297

(SD 35%) to 357 kg DM ha^{-1} (SD 35%), when the interval was shortened from 45 to 15 days.

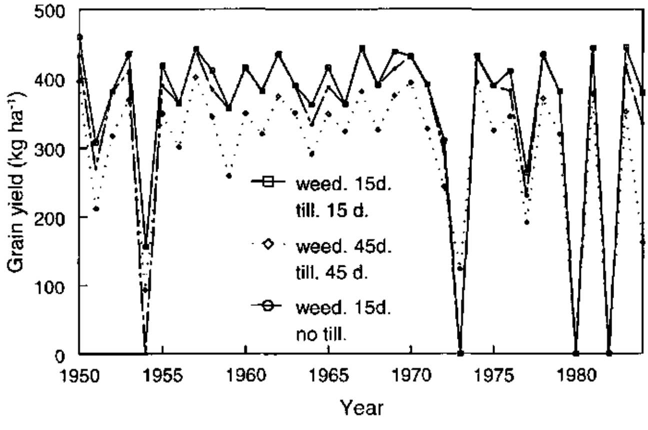

Fig. 50. *Actual (weedy) grain production (minimum of water or nutrient limited).*

So, according to this study, water conservation should not be our first priority but an increase of external inputs. The results obtained with this study show that external inputs in the form of fertilizer have the highest impact, followed by the weeding, as can be seen clearly in Table 36 when comparing water limited yields with actual yields.

Even with inputs and water conservation tillage, the yield gap between achievable and the zone's potential grain production of 1500 kg grain ha^{-1}, remains large. This is partly caused by the fact that the tillage reduces the runoff only from 37% till 26%. When more rigorous water conservation can be achieved and runoff completely be reduced, the water limited production could be increased till 861 kg grain ha^{-1}. For the remainder of the yield gap the application of secure water harvesting or irrigation is needed. Another justification for water harvesting or irrigation is the large annual variation of the rainfed production.

4.6.5. Limitations and recommendations

(1) DUET.91 provides for a dynamic simulation of crop growth as a function of available water. Nutrient requirements and availability are not treated in a dynamic way. According to DUET.91 improved water availability early in the season leads to an increase in vegetative growth. One may wonder whether this is realistic under low nutrient availability conditions. However, it is commonly accepted that the majority of nutrients is liberated by

mineralization of the soil's organic matter early in the season in the form of a flush. Therefore, the implicit assumption of a high nutrient supply early in the season seems to be allowed.

(2) Weather data include daily amounts of rainfall. However, often no information about the duration or intensity of rainstorms is available. This makes it not possible to match rainfall with the (limited) infiltration capacity of the soil in a direct way. In DUET.91 an empirical relation between the size of the shower and its intensity was used to estimate the fraction of runoff of that shower for a given infiltration rate of the soil.

(3) Data of the soil's infiltration capacity as a function of cumulative amount of precipitation are scarce and need to be determined in the Sahel using portable rainfall simulators.

(4) After tillage, creating a dry soil mulch, the actual soil evaporation is reduced and its value is gradually restored as a function of the cumulative rainfall after tillage. This is not yet included in DUET.91. A similar but inverse functional dependence as used for the effect of tillage on infiltration, with regards to soil evaporation should be included.

(5) Tillage increases the soil's susceptibility for erosion. Each tillage operation may remove part of the nutrients that come available from the mineralization of organic matter (module 3) as well as from externally applied fertilizers. Although this amount may seem small on the short-term, an increase in the number of tillage operations over a period of tens of years may show a dramatic effect on the stock of soil nutrients.

(6) In the simulation over a series of years, this possible reduction in nutrient availability or deterioration of the physical condition of the soil was not taken into account. This aspect should be included in future work.

4.7. Case 6. Crust formation on sandy soils in the Sahel: tillage and its effect on the water balance

4.7.1. Introduction

For many years, the causes of the low agricultural productivity of the Sahel region have been studied. It was common belief that water shortage was the main reason. However, Penning de Vries and Djitèye, (1982) showed that for natural pastures in the southern part of the Sahel, the main production-limiting factor is a shortage of plant nutrients.

The question remains whether this also applies for cereal crops which are grown in the same area. It was shown in case 1 that fields under millet (*Pennisetum glaucum* (L.) R.Br.) in Mali show higher losses of rainwater by runoff compared to fields under natural pasture. The resulting lower availability of water, and the longer growing cycle of millet support the theory that water shortage is the main cause for low productivity. indeed, a field study of tillage practice on a Malian farm (Hoogmoed and Kievit, 1981), suggests that local farmers realize that the most important reason for tillage is enhancing infiltration.

In certain Sahelian areas in Senegal and Niger, millet is grown on very coarse sandy soils where runoff seldom occurs. However, in these soils, the water holding capacity is so low that rainwater rapidly drains to layers below the root zone. These losses also reduce the availability of water for the plant. Where this is the case, it is not likely that tillage will have a positive effect on the water availability.

This study emphasizes, both theoretically and experimentally, the positive effect improved tillage may have on the water balance of a millet crop where, under conventional tillage, runoff causes a significant loss of available water.

Firstly, the water balance of local natural pastures is briefly reviewed to indicate where tillage will modify this balance. It was shown in case 1, that the sandy Sahelian soils are very sensitive to crust formation, due to the specific soil and climatic characteristics. The crust, which is permanent under natural pastures, dominates the infiltration of rainwater into the soil. Obviously, since tillage has a direct effect on the crust, this manipulation will completely change the infiltration characteristics of the soil.

Secondly, quantitative measurements of infiltration into tilled and untilled (natural) soil are discussed. It is important to know how long the tillage effect lasts, i.e., when reconsolidation of the topsoil and slaking of the surface have lowered the infiltration capacity to its initial value or even lower. Based on the measurements, a simple model was chosen, describing the infiltration process for crusted, as well as for tilled, soil. With this descriptive model, although derived from few data with limited accuracy, the overall seasonal effect of tillage operations is predicted by combining the information on infiltration-tillage interactions with the rainfall analysis described in case 1.

Finally, the effect of the water balance, as changed by tillage, on millet production in this part of the Sahel is estimated. It must be stressed here that this estimate could be only very rough. This particular study informs in a general way about the specific role of tillage in a semi-arid zone such as the Sahel, and does not present a technical tillage experiment as such. In this respect it stresses the need for further on-farm research.

4.7.2. The crop soil water balance in the Sahel

Plants can only grow if their stomata are open, allowing photosynthesis. As a passive result of the opening of stomata, plants lose water by transpiration. If there is no water available in the soil, stomata close and growth stops. Hence, the availability of soil water is, amongst others, an important factor which determines plant growth and plant production.
Whether water is available for plants depends on soil factors (moisture content at the wilting point, soil depth, etc.) and plant factors (rooting depth, hydraulic resistance, plant root system, etc.), and on the amount of water in the topsoil. The latter quantity varies from day to day as a result of infiltration, transpiration and soil evaporation. In general, soil and water conditions in the Sahel are such that percolation below the root zone or capillary rise from a water table can be neglected. All processes which add or deplete water from the soil contribute to the soil water balance. These processes can be studied and described on various time scales. If tillage effect on infiltration is the subject, the time scale will be such that individual rain showers can be considered. If, on the other hand, interest is focussed on the effect of a tillage practice on cereal production, the time scale has to be such that a complete growing season can be considered. In the following chapter, the principal components of the soil water balance of natural untilled soils will be briefly discussed in a quantitative way. For a detailed description the reader is referred to Stroosnijder and Koné (1982).

Infiltration
Infiltration of rainwater into the soil depends on the duration of the storm and the decrease in infiltration rate of the soil with time. Earlier, it was shown that Sahelian rainstorms are often of short duration and high intensity. Since soils under natural pasture are permanently crusted, ponding of water on the soil surface often starts soon after the beginning of a storm. Therefore, for Sahelian conditions, the amount of rain that can infiltrate can be calculated using theoretical relationships which assume ponding as the prevailing boundary condition.

Runoff
Water will collect on the soil surface when the rain intensity is greater than the infiltration capacity of the soil. The surplus rain first fills up the surface storage, which consists of the closed depressions on the soil surface and then builds up

a hydraulic head, the so-called surface detention, before surface flow starts. In experiments it was measured that, under natural conditions (no tillage practices), the total amount of surface storage and detention did not exceed 1 mm.

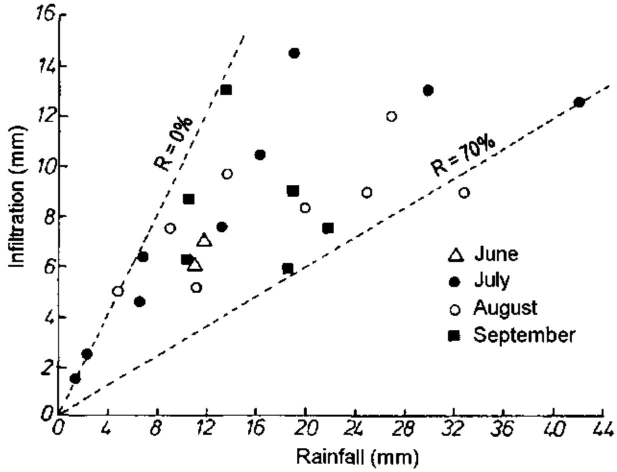

Fig. 51. *Relationship between amount of infiltration and storm size, for runoff values of 0 and 70%, Niono 1978.*

A complicating factor in the description of infiltration is the moisture status of the soil at the moment a new storm starts. Three cases are distinguished: dry soil, air-dry in the top 30 cm; wet soil, at about field capacity (1 day after a storm); and moist soil, an intermediate situation, which occurs between 5 and 10 days after a storm. It was shown in case 1 (Fig. 16) that for permanently crusted soils the effect of a different initial moisture status is such that for the infiltration rate as a function of time, a seasonal average relationship may be used. No doubt errors are introduced due to this simplification. However, using this simplification over the whole growing season gave results which could be verified by measurements and simulation.

Since infiltration is closely related to storm size and duration, parameters which vary strongly within the season and also from year to year, runoff may vary from 0 to 70% of individual showers (Fig. 51). Although elaborate analyses of rainfall and infiltration properties of the soil offer good estimates of runoff, a more simple approach may be used as well. An average annual runoff percentage can often reasonably be estimated in the field by the 'type 1' method to be described later. For the calculation of runoff of individual showers, the average percentage may be used as a basis and corrected for different storm-size classes (Stroosnijder, 1982).

Evaporation

From measurements on crusted soils during the growing seasons of 1978 and 1979, it appeared that potential evaporation of bare soil may be related to the evaporation according to Penman (i.e., 70% of the open pan evaporation under local conditions). According to Stroosnijder and Koné (1982), the cumulative actual evaporation during the growing season ΣE (mm) between two showers equals

$$\Sigma E = f(\mathrm{LAI}) \times \mathrm{PEVAP} + 3.5\,(t^{0.5} - 1)$$

where f(LAI) is the correction term depending on the leaf area index (LAI, dimensionless), PEVAP = potential evaporation (mm) and t = time (days).
f(LAI) only affects ΣE during one day after a rainfall, so, later the cumulative evaporation is proportional to the square root of time. The proportionality factor of 3.5 was constant for a variety of soils, ranging from sand to clay, and was also found for sandy soils in Senegal (Hall and Dancette, 1978). Total seasonal evaporation for the south-Sahelian region calculated according to the above simple model showed that the average daily evaporation over the growing season decreases from 2.5 mm day for bare soil to 1.5 mm day for a soil with a vegetation cover characterised by LAI = 1.

Transpiration

Most Sahel plant species (including millet) are of the C4 photosynthetic type which use soil water very efficiently; their transpiration coefficient under the prevailing climatic conditions averages about 200 kg water per kg dry matter.

Table 37. *Water balance of natural vegetation (mm).*

Total rain in 1978	490
Rain in growing season	415
Runoff (measured, 40%)	165
Infiltration (415-165)	250
Evaporation (measured)	200
Evaporation (calculated)	160
Transpiration (200-160)	40
Available water left in soil (250-200)	50

Natural pastures in the south Sahel produce an average above ground biomass of 2 t ha^{-1} and have a below ground dry matter production of 1 t ha^{-1}.
Consequently, 60 mm of soil water is required for transpiration. In the same region, under average climatic conditions and average agronomic practices, millet yields 1.8 t ha^{-1} of above ground dry matter and 0.6 t ha^{-1} dry matter below the soil surface at flowering (about 15 September). This means that, to produce a reasonable millet crop, about 50 mm of water must be available for transpiration.

Example of the water balance of natural vegetation

Natural pastures germinate soon after the first rains, mostly in late May or early June. However, in 1978, due to very dry conditions in June, all previously germinated plants had died and only in the second decade of July was a new germination flush observed. Since flowering date is fixed at 15 September because of strong photoperiodic sensitivity, there were only 50 days for growth and total dry matter production was about 2 t ha^{-1}. From the water balance for the growing season (Table 37) it appears that the natural vegetation was not able to use all available water in the soil and left 50 mm unused. In other research (Penning de Vries and Djitèye, 1982) it was found that this was caused by lack of nutrients, in particular nitrogen and phosphorus.

4.7.3. Tillage-infiltration interactions

The permanent presence of a crust on the natural soils allows use of a simple expression for the infiltration process (case 1). Tillage interacts strongly with this crust, so a method to measure and explain the tillage effect on crust and infiltration should be found. Since a crust restores quickly under raindrop impact, the tilled soil will behave increasingly more as a crusted soil and will approach the natural situation.

Therefore 5 various methods for measuring infiltration are discussed, assessing their ability to reflect crust presence and/or formation. Results for tilled soils will be compared, as a reference, with results for natural untilled soils.

Materials and methods

Two types of field methods to measure water infiltration were used.

(1) Measurement of the total amount of infiltrated water at the end of a wetting process. This type of measurement is very simple and cheap. It is usually performed after natural rain showers.

(2) Measurement of the rate of infiltration in the course of time. This method involves more elaborate measurements and requires better-controlled conditions in the field. Therefore, this method is executed mainly in combination with artificial rainfall.

Type 1 measurements were performed in two ways.

(1a) Direct measurement of the amount of soil moisture with a neutron probe (depth and surface probe) at a number of (field) observation points during the whole growing season. Moisture readings before and immediately after a shower permit calculation of the volume of water infiltrated.

(1b) Measurement of runoff from small plots (a few m^2). Subtraction of the runoff volume from the volume of rainfall (measured in the immediate vicinity of the plots) gives the volume of water infiltrated.

The above measurements were executed only during the rainy season, making use of natural showers. Measurements of type 1a were carried out during four

seasons (1976-1979) and those of type 1b during 1978 and 1979.
Three kinds of type 2 measurements were executed.

(2a) In 1976 and 1977, double-ring infiltrometers (0.05 m^2) were used. Compared to results obtained with method 1a, based on the measurements related to natural rainfall events, values for the infiltration rate were more than one order of magnitude higher. Use of these high infiltration rate values in calculation of the moisture content during the entire rainy season gave far too high results as compared with actually measured moisture contents. The ring infiltrometer method apparently yielded unrealistic values for the infiltration capacity. This was probably caused by: (1) breaking the crust by inserting the steel rings; (2) no 'recrusting' due to lack of natural rain with a high kinetic energy (raindrop impact); (3) the positive water head of about 1 cm over-ruling the hydrophobic character of the crust; and (4) the possibility for free air to escape during infiltration. Natural crusts often show a vesicular structure and some soils even show a very soft porous toplayer which may be attributed to compressed air collecting just below the crust.

(2b) In 1978, infiltration was measured with a simple drip-type rain simulator. The soil surface (0.5 m^2) was wetted by artificial rain with a high intensity, but, as the drops fell over a distance of only 1 m, the kinetic energy was far too low. This was compensated by increasing the drop size from a median 2.5 mm to 5.6 mm diameter (Hoogmoed and Stroosnijder, 1978), however, the kinetic energy remained considerably lower than that of natural rainfall. Consequently, although the results with this method were better than with method 2a, infiltration rates obtained were still higher than those determined with methods la and lb and, therefore, considered to be not realistic.

(2c) In 1979, an elaborate rainfall simulator was used which produces rain with a kinetic energy comparable to that of natural rain (cf. case 1). Results obtained with this equipment were in the same order of magnitude as deduced from the type 1 measurements.

Type 2 measurements were performed on tilled soils under millet as well as on permanently crusted soils under natural vegetation. Tillage was performed by ploughing with common, small, animal-drawn, mouldboard ploughs (working width, 25 cm) to a depth of about 15 cm, in a soil which was moistened by the first rains of the season to ploughing depth. Ridges were made manually with a hoe (height, 15-20 cm; distance between ridges, 50 cm).
Measurements of the infiltration rate were fitted to two types of equations. First, an empirical exponential equation proposed by Horton (1940)

$$IR(t) = (IR_i - IR_f)\, e^{-\alpha t} + IR_f \qquad (1)$$

where $IR(t)$ = infiltration rate as a function of time (mm min^{-1}); IR_i = initial infiltration rate at t = 0 (mm min^{-1}); IR_f = final infiltration rate at $t = \infty$ (mm min^{-1}), this value is supposed to be equal to the saturated hydraulic conductivity; α =

empirical constant. Second, a short version of a theoretical sorptivity equation proposed by Philip (1957)

$$IR(t) = 0.5\ S\ t^{-0.5} + b \qquad (2)$$

where S = sorptivity of the soil for water (mm $min^{-0.5}$); b = a term which reflects gravity (mm min^{-1}), but is not equal to the saturated hydraulic conductivity; this term may also be written as $\beta \times IR_f$, where β has a value between 0 and 1.
When the above equations are integrated with respect to time, the cumulative infiltration, CI (mm), is obtained. Most rain showers are of high intensity but of short duration and the saturated conductivity of most crusted soils is very low. Therefore, an approximate, but very simple equation may also be used to characterize the cumulative infiltration, i.e.

$$CI = S\ t^{0.5} \qquad (3)$$

where S = sorptivity (mm $min^{-0.5}$); and t = time (min). This sorptivity is, in fact, a proportionality factor, which varies from >10 mm $min^{-0.5}$ for coarse sand to 0.5 mm $min^{-0.5}$ for heavy clay (Stroosnijder, 1976). It reflects the soil's power to absorb water (as a sponge) and neglects gravity. S is not a unique value but a function of the initial soil wetness.
Equations (1)-(3) contain a decreasing number of parameters, from three in eqn. (1) to one in eqn. (3). The advantage of the one parameter equation (eqn. 3) is that its parameter S can be determined from infiltration measurements type 1.

Results

Infiltration in freshly tilled soil
Infiltration in a freshly tilled soil is more difficult to describe than that in a permanently crusted soil, because in a tilled soil, due to rainfall, the crust is gradually restored. Thus, the infiltration rate is not only a function of the actual moisture condition at the soil surface and of the initial soil wetness, but also of the crust history. Fig.52 (Hoogmoed, 1981) demonstrates that the infiltration rate of freshly ploughed (dry) soil is very high. Artificial rain, applied at a constant rate of 0.82 mm min^{-1} did not produce runoff for more than 90 min. A second wetting took place one day after the first wetting and a third wetting 11 days after the second one. From the curves of these three wettings and the curve for dry, permanently crusted soil, it can be concluded that each shower contributed to the build up of a new crust and that at the third wetting the effect of ploughing had almost disappeared. When, after ploughing, ridges were made by hoe, similar infiltration rate curves (not shown) as for ploughing only were obtained.

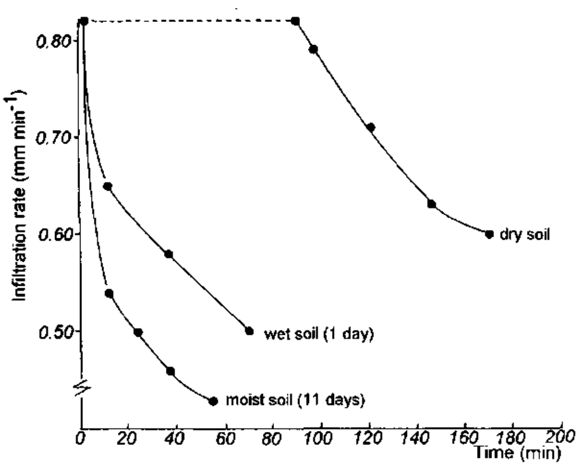

Fig. 52. *Measured infiltration rates as a function of time of wetting for different conditions of the tilled (and recrusted) soil.*

In Fig. 53, in contrast to Fig. 52, the infiltration rate is not plotted against time, but against the cumulative volume of rain applied. It appears that during the onset of each next rain there is a very short period with the usual high infiltration rate but then the rate drops quickly to values which are below those observed during previous wettings.

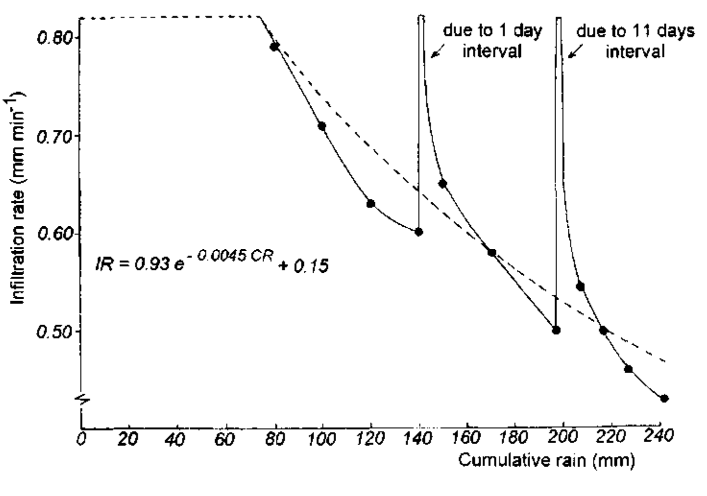

Fig. 53. *Measured infiltration rates (IR) as in Fig.52, replotted as a function of cumulative (artificial) rain (CR).*

The limited number of measurements does not indicate whether the cumulative amount of rain applied or the number of wetting/drying cycles is the most important factor in crust formation. Since, in our experiments, only one rain intensity was used (0.82 mm min^{-1}), also the effect of different rain intensities is unknown. From Israeli research (Seginer and Morin, 1970; Morin and Benyamini, 1977; Morin et al., 1981), however, it appears that indeed the cumulative volume of rain (quite independent of intensity) is the most important crust-forming parameter. Consequently, a variant of Horton's equation (eqn. 1) was proposed by Morin and Benyamini (1977):

$$IR(t) = IR_f + (IR_i - IR_f)\, e^{-\alpha\, CR} \tag{4}$$

where CR indicates the cumulative amount of rain (mm). When applying this equation to the individual showers, as in Fig. 51, the following would be obtained for the three curves (best fits):

Dry soil: $$IR(t) = 22.0\, e^{-0.017CR} + 0.62 \text{ (mm min}^{-1}\text{)} \tag{5}$$

Wet soil: $$IR(t) = 0.26\, e^{-0.052CR} + 0.51 \text{ (mm min}^{-1}\text{)} \tag{6}$$

Moist soil: $$IR(t) = 0.23\, e^{-0.072CR} + 0.43 \text{ (mm min}^{-1}\text{)} \tag{7}$$

However, the effect of rain duration and very high intensities on the above equations is unknown. As a further simplification, only one equation can be used, in which CR is defined as the total amount of rain fallen since the tillage operation. In this way one obtains for the 'enveloping curve' in Fig. 53 the following equation:

$$IR(t) = 0.93\, e^{-0.0045CR} + 0.15 \text{ (mm min}^{-1}\text{)} \tag{8}$$

This curve was fitted with an average value for the ultimate final infiltration rate at the moment the crust has been fully restored, as found in the experiments on undisturbed soil: $IR_f = 0.15$ mm min^{-1}.
Equation (8), which contains only one parameter *(CR)*, will be used in the last part of this communication to calculate the seasonal effect of a tillage practice on the water balance.

Infiltration in recrusted soils

A large number of sorptivity values *(S)* were determined by using methods 1a and 1b, on various soil types near Niono. The two methods virtually gave the same results, therefore, the limitation of a small catchment area in the type Ib measurements did not significantly influence infiltration and runoff. Sorptivity values averaged over the season (i.e., with different initial moisture status) ranged from 0.5 mm $min^{-0.5}$ for clayey soils to over 2.5 mm $min^{-0.5}$ for the

coarsest sand soils (Stroosnijder and Koné, 1982). Sorptivity values for the (dry) loamy fine sand discussed in this paper varied from 0.75 to 1.5 mm $min^{-0.5}$ depending on the condition of the crust, kind of vegetation, etc.
The results of the experiments with the rainfall simulator (method 2c), were analysed using the two infiltration rate-time relationships (eqns. 1 and 2). The best fits of the exponential integrated Horton (1940) and sorptivity equations of Philip (1957) are for the exponential fit:

Dry soil: $CI(t) = 3.40\ (1 - e^{-0.10t}) + 0.18\ t$ (mm) (9)

Wet soil: $CI(t) = 1.24\ (1 - e^{-0.21t}) + 0.11\ t$ (mm) (10)

and for the sorptivity fit:

Dry soil: $CI(t) = 1.27\ t^{0.5} + 0.12\ t$ (mm) (11)

Wet soil: $CI(t) = 0.70\ t^{0.5} + 0.06\ t$ (mm) (12)

The correlation coefficients were about the same for both fits (Hoogmoed, 1981), therefore, there is no large difference in 'accuracy of fit' between these formulae. Equation (1) is preferable for large t values since the equation gives the right final infiltration rate, whereas eqn. (2) has an asymptotic value that gives only a fraction (β) of the real final infiltration rate. From the actual values of the curve fit this fraction can be calculated as follows. For dry soil $IR_f = 0.18$ (eqn. 9) and $b = \beta \times IR_f = 0.12$ (eqn. 11). For wet soil these values are 0.11 and 0.0, respectively. Thus, β = 0.67 for dry soil and 0.55 for wet soil, values which are often found in practice (Stroosnijder, 1976). Lafforgue (1978) gives equations similar to eqns. (9) and (10) for clayey-sandy soils from Burkina, i.e.

Dry soil: $CI(t) = 13.0\ (1 - e^{-0.107t}) + 0.21\ t$ (mm) (13)

Wet soil: $CI(t) = 2.9\ (1 - e^{-0.199t}) + 0.19\ t$ (mm) (14)

Equations (9) and (10) and those of Lafforgue (eqns. 13 and 14) show the same difference in infiltration behaviour between a dry and a wet soil. The parameter α reflects the contribution of the absorption forces in *CI*. From dry to wet, α values double, therefore, the time during which absorption forces contribute to *CI* is halved. The above equations also show that, as expected, the final infiltration rate is only slightly influenced by initial soil wetness.

It is of interest to compare the values for the infiltration rate as measured with the elaborate rainfall simulator with those of method Ia, which was supposed to be the method which most accurately simulated the real situation.

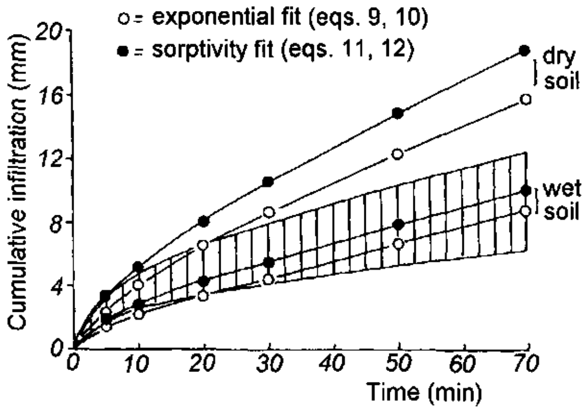

Fig. 54. *Measured cumulative infiltration as a function of time of wetting, for a permanently crusted loamy sand under natural vegetation at Niono (Mali). (method 2c.) Shaded area indicates the variation of cumulative infiltration as determined at the end of natural showers during the rainy seasons of 1976 to 1979 (methods 1a and 1d).*

In Fig. 54 such a comparison is made in terms of cumulative infiltration (*CI*). The best fits to values obtained with the rainfall simulator are given for the two extreme cases, dry and wet soil. Also the variation in values found with methods 1a and 1b is indicated. It must be noted that these latter values are averages for a full season, i.e., for dry, wet and intermediate situations. The most important part of Fig. 54 is the curve for the period between 0 and 30 min, because almost all natural showers have a duration within this interval. On dry soils the values found with the rainfall simulator are still somewhat higher than those found by the other methods, but on wet soils the rates for infiltration are within this range. The deviations give rise to the conclusion that the rainfall simulator is a powerful tool for quantitative infiltration measurements in the field during the long dry season. However, if measurements during the short rainy season can be made, methods of type 1 are preferable; they are supposed to be the most accurate (field scale), simple (moisture and rainfall measurements only) and least costly.

4.7.4. Tillage-water balance-productivity interaction

First a brief description of the seasonal water balance of a millet crop under conventional tillage is given. Then infiltration equations reflecting tillage effects are combined with a rainfall analysis as given in case 1. Finally, an estimate of the resulting increase in crop production is explained.

Water balance of millet under conventional tillage

During the 1979 growing season, soil and water aspects in the production of a millet crop at a local farm near Niono were studied. The soil of the field under observation was similar to the soil of the experimental area.
Rainfall in 1979 was only 80% of average rainfall and resulted in late ploughing and sowing. These operations were carried out in a period from 60 to 30 days before 15 September, the average flowering date. Since the minimum period between sowing and flowering is supposed to be 50 days for Malian lines of millet (ICRISAT, 1981b), production potential was low. This was illustrated by an average grain yield on this farm of only 326 kg ha^{-1}. The water balance, partly measured and partly estimated for the millet field of this farm is shown in Table 38.

Table 38. *Water balance of millet (mm).*

Total rain in 1979	449
Rain in growing season[a]	300
Runoff (measured, 50%)	150
Infiltration (300-150)	150
Evaporation at 2 mm day (estimated)	110
Available for transpiration	40

[a] 55 days preceding 15 September

Contrary to the case of the natural pastures, there was a negligible amount of available water left in the soil, indicating that even for the low yield, the millet crop used nearly all water available throughout the season.

Effect of improved tillage on the water balance

Calculation of runoff was performed for four different situations:
(a) No tillage operations and a surface storage and detention (SS) value of 1 mm, simulating the situation of a field with a crust and no special surface configuration;
(b) Tillage operations and a low *SS* value of 1 mm, simulating a smooth surface as created by conventional tillage;
(c) Tillage operations producing a high *SS* value of 10 mm, simulating the situation as would apply just after improved tillage;
(d) No tillage operations and a high *SS* value of 10 mm, simulating the (re)crusted soil (possibly quite some time after tillage) with the special surface configuration created by the farmer.

Using the actual Niono rainfall data for three consecutive years (1977-1979) and the infiltration data for untilled soil (eqns. 9 and 10), for situation (a) seasonal runoff values as high as 41, 38 and 39% of rainfall was calculated (see Table 39). These values are of the same order of magnitude as the measured seasonal runoff on this soil type. In situation (b), conventional tillage was assumed to be performed after the first rain showers of the season, and the infiltration equation for tilled soil was used (eqn. 8).

Table 39. *Absolute and relative amounts of runoff at Niono for different tillage practices and surface storage values (SS), for three growing seasons.*

Year	Rain (mm)	Tillage treatment	Runoff			
			SS = 1.0 mm		SS = 10.0 mm	
			(mm)	(%)	(mm)	(%)
1977	368	Tillage	76	18	11	3
		No-till	155	41	48	13
1978	271	Tillage	49	18	19	7
		No-till	104	38	33	12
1979	361	Tillage	80	22	38	11
		No-till	141	39	70	19

Calculated runoff was only half of that obtained in situation (a). The effect of tillage is limited since a new crust is formed rapidly so that infiltration rate and surface storage (roughness) will rapidly drop to low values. It seems that the effect of conventional tillage is too shortlived to be considered as an effective tool to increase infiltration and reduce runoff. Runoff was also computed assuming the creation of a large, permanent surface storage, i.e., situations (c) and (d). As Table 39 shows, a surface storage of 10 mm would, without, or long after crust-destructing tillage (case d), decrease runoff to 12-19%. Situation (c) gives the best results, but this situation applies only to tillage practiced at the beginning of each season, at the same time as in situation (b). It was found by optimization, that, when in a no-tillage situation surface storage would be increased to 20 or 30 mm, virtually all runoff could be prevented.

These results indicate that tillage practice should aim at a (semi)permanent increase in surface storage rather than in breaking the surface crust only. One system, tied ridging or basin-tillage, was tried in an experiment. This system is not yet used in the Sahel, but was developed quite some time ago in Africa (FAO, 1966) and is becoming increasingly popular in the U.S.A. (Idike et al., 1982) and Israel (Rawitz et al., 1983). Ties in the furrows of the existing ridge system in Mali can be made manually. Because of the absence of tractors, no technical problems occur (traffic in the furrows for crop maintenance and harvest). The functioning of the system is most important during the beginning of the rainy season, and the gradual flattening of the ridges by subsequent rains reduces the risk for prolonged periods with water stagnating in the depressions (aeration problems).

On a sloping part of the farmer's field at Niono (slope about 2%) ties, constructed with a hoe at a distance of 4 m, gave an estimated surface storage of 40 mm. During the period of measurements (about 2 months), no runoff was observed, except for the heaviest shower of the season (80 mm), which did some damage to the ties.

Effect of improved tillage on millet production

The effect of a reduction in runoff on crop production can be estimated with the help of the rainfall analysis given in case 1. It was assumed that with the present conventional system of soil tillage, average runoff amounts to 50%. Assuming an average evaporation of 2 mm day^{-1}, this means that only 10-day periods with more than 40 mm of rain are wet enough to start a crop. However, if all runoff can be prevented, as seems possible with tied ridges, already 20 mm of rain in a 10-day period is enough to start crop growth. Consequently, sowing can be done earlier, which increases the average length of the growing period. It was assumed that for growing periods ranging from 50 to 90 days between sowing and flowering, the grain production (without substantial fertilization) can be estimated as follows

Y (kg ha^{-1} grain) = 10 × (number of days from sowing to flowering - 20)

Thus, the effect of a runoff-reducing tillage system which results in a 20 days' longer vegetative growth may be as large as 200 kg ha^{-1} grain. With an average production of 500 kg ha^{-1}, this means an increase in yield of no less than 40%. For two locations, Niono at the south border of the Sahel and Hombori, which is close to the north border of the millet growing area of the Sahel, the average length of the vegetative growing period was estimated for a normal year (50% probability of surpassing) and for a dry year (90% probability of surpassing) for two extreme values of runoff (Table 40).

At Niono a complete prevention of runoff prolongs the vegetative period in a normal year by 30 days and in a dry year by as much as 40 days. In addition to a large increase in water available for transpiration (and thus for growth) this may be called a dramatic effect, which in dry years can possibly increase millet grain production from a bare zero to a subsistence level at least. This conclusion also holds for Hombori although here the effect on the length of the vegetative cycle is less spectacular than the effect on the availability of water for transpiration.
It should be noted that if so much water is gained, for an optimal use of this water the use of fertilizers (in particular P and N) will be necessary. However, the reverse is also true: under current tillage practices the use of fertilizer is marginal since water availability is the main production-limiting factor. The above results thus prove once again that one agronomic innovation (such as the use of fertilizers) will only be effective in combination with other agronomic innovations, of which better tillage is only one feature.

Table 40. *Length of the growing season and related water balance for north and south boundaries of the millet growing area of the Sahel during a 'normal' and a 'dry' year as a function of relative runoff (R).*

	'Normal' year		'Dry' year	
	R=50%	R=0%	R=50%	R=0%
Hombori (15 °17'N)				
Start growing season	1 July	15 June	27 July	4 July
Flowering date	15 Sept	15 Sept	15 Sept	15 Sept
Length vegetative phase (days)	75	90	50	70
Rain in vegetative phase (mm)	350	380	200	250
Runoff (mm)	175	0	100	0
Evaporation (2mm day) (mm)	150	180	100	140
Available for transpiration (mm)	25	200	0	110
Niono (14 °15'N)				
Start growing season	3 July	1 June	27 July	17 June
Flowering date	15 Sept	15 Sept	15 Sept	15 Sept
Length vegetative phase (days)	75	105	50	90
Rain in vegetative phase (mm)	400	475	140	300
Runoff (mm)	200	0	70	0
Evaporation (2mm day) (mm)	150	210	100	180
Available for transpiration (mm)	50	165	-	120

4.7.5. Discussion

It is well understood in this context that the optimistic view based on the results discussed above are based on a theoretical analysis of rainfall distribution and that the 'real' situation may be considerably less ideal than suggested. However, perspectives are such that further research is strongly recommended. In this respect, on-farm operational research is urgently needed. The experiments should be fully analysed by tillage, soil water and crop specialists, enabling the verification of whether the above suggested change in tillage practices will indeed contribute to a solution of Sahelian food shortages.

4.7.6. Conclusions

(1) A rainfall simulator with a rotating disc, which produces rain with a realistic kinetic energy, is a well-suited tool for research on the soil water balance under Sahelian climatic conditions.

(2) On tilled soils, the relationship between infiltration rate and cumulative rain may be expressed by a one-parameter equation.

(3) During the growing period in 'normal' years, the natural vegetation does not use all water available in the soil. However, for a millet crop water is the limiting factor for increasing yields.

(4) In the early stages of the growing season, runoff can be reduced by increased surface storage brought about by special tillage measures such as tied ridging. This allows earlier sowing of a millet crop without (statistically) extra risks, resulting in higher yields.
(5) A permanent tied-ridging system, creating a surface storage of 20 - 30 mm, is more effective in runoff reduction than the conventional system of seasonal ploughing.

5. DEVELOPMENT OF TILLAGE SYSTEMS FOR SOIL AND WATER CONSERVATION

5.1. Low energy input situations (e.g. West Africa)

It is impossible in this context to treat in depth all factors playing a role in the implementation of soil tillage systems (and particularly those based on animal draught technology). However, the most relevant ones are given here and where possible, their importance for soil and water conservation will be assessed.

Manual labour, scope for improvements

There is not much room for improvement of the situation where only manual labour is available.
In terms of tillage tools, an amelioration is possible by using better materials for the typical instruments such as the hoe or spade (steel instead of iron in order to produce tools which do not wear quickly and have sharper cutting edges). This may not cause a strong reduction in the strain placed upon the farmer, but is sometimes seen as a realistic approach towards improving the situation (Spencer, 1985). For weeding hoes, the use of long handled tools will alleviate the burden of the users (usually women), but social acceptance (by the men) is often found to be serious barrier (Muylwijk and Smetsers, 1996).

With regard to tillage systems, a reduction of the energy expenditure for the farmer can be achieved in choosing a form of reduced or site-specific tillage, which may range from building permanent ridges, beds or mounds, strip-tillage up to complete zero-tillage, limiting soil manipulation to opening the soil locally for seed placement, or even to planting seeds directly in the undisturbed soil using a planting stick or special punch-planter. Such reductions are in fact commonly applied: digging to a depth of 10-15 cm with a spade or hoe requires 200 to 250 man-hours per ha, which is impossible to realise for low-yielding cropping situations. Instead, superficial hoeing ('cleaning' the field for seedbed preparation) may be done which requires 25-30 hours, or planting directly in the undisturbed soil. In that case the planting operation may take no more than a total of 6-7 hours of a team consisting of a man opening up the soil and a woman or child doing the planting. The consequence of the latter system is that weeding times become larger.
Semi-permanent surface configurations for soil and water conservation also incorporate a reduced tillage approach (Vlaar, 1992; Unger, 1984; Hudson, 1987). Technical details of these systems are given in 3.2.2.

Use of draught animals

Introduction or extension of the use of animals (Animal Draught Power, ADP) for tillage appears an attractive alternative to hand labour and a logical phase possibly leading to motorization. The change from hand labour to animal traction or motorization, however, implies a different nature of the tillage operations. From site-specific tillage with the human energy as a main constraint, there is a shift to the use of other implements (the mouldboard plough) which is used mainly in full-field operations. In practice, a large number of serious restrictions of widely ranging nature can be encountered. Eicher and Baker (1982), in a comprehensive survey, discuss the wide range of technical and socio-economic problems involved in agricultural development in sub-Saharan Africa. More specific information on ADP in Africa is given e.g. by Munzinger (1982) and Starkey (1989).

Animals, numbers required, availability, feeding. In Africa, the ox is the most animal used for traction. Horses are vulnerable to the sleeping sickness, caused by the Tsetse fly, and they are generally less resistant to work under difficult (hot, humid) climatic conditions. Donkeys are found as draught animals, but their use is usually limited to transport and light weeding due to the lower level power they can generate.

Although the increase in capacity is enormous when hand labour is replaced with animal draught (at least 5-fold), the aforementioned change in the nature of the tillage operations (from site-specific to full-field) is a reason that the total number of animals needed for the application of animal traction in West Africa is substantial. For a common situation where a field is to be ploughed as soon as possible after the onset of the rainy period, it may be assumed that mouldboard ploughing requires approx. 18-20 hours per ha with one pair of animals. One working day under tropical conditions for ploughing counts 6 hours maximum, so tillage of one ha requires 6 animal-days.

In the typical West-African Sudan-savanna situation, the number of available days for ploughing of light soils, where there is virtually no 'wet' workability limit, ranges from 10 in the northern savanna region up to 25 in the southern region. The workable period is assumed to end due to the lack of moisture sufficient for seed emergence. These values are based on the rainfall distribution in the beginning of the rainy season, assuming a latest sowing time in the north of July 1, in the south July 25 (case 2; Hoogmoed, 1986). For heavier soils with a higher water holding capacity, the workable period will start one or two days later, but may be slightly longer. Since draft requirements also will be higher, the total animal-requirement will not change much.

So this leaves a maximum 'tillable' area of 1.66 ha per animal in the north and 4.16 ha per animal in the south. These figures were also found for farms with animal traction in Senegal, where 1 pair of oxen was able to manage 8 ha (1 pair of cows 6 ha, 1 donkey 3 ha, 1 horse 4.5 ha. It can also be assumed that for feeding, at least one ha is needed per animal, and 5 ha more to allow herds big enough to ensure sufficient supply (reproduction) of draught animals. The conclusion can be drawn that without additional feeding and import of draught animals, these regions are not able to generate sufficient numbers of animals when traditional 'full-field' tillage is to be applied.

Expansion of area vs intensification. The introduction of ADP has been reported to lead to an increase of the area under cultivation in situations where land was still available. In such situations, the soil and water conservation effect is negative: land is taken under production which is probably of a lower quality (less SOM, shallower, steeper slopes), and risks for degradation and erosion are high. From a farming point of view, expansion of the area will increase the labour peak caused by weeding (when this activity is not going to be mechanised).
When ADP replaces hand labour without extension of the cropped area (intensification), then the productivity per person will increase. The effects will be positive with respect to soil and water conservation, infiltration may be improved by deeper soil disturbance (Nicou et al, 1993) and better and earlier crop stands give more protection against rainfall.

Limitations in draught output. The draught or tractive effort that animals are able to produce, is limited. Many factors play a role in determining the maximum or average levels: male animals (usually oxen) are stronger than cows, there is a big difference between breeds (in West Africa, Zebus e.g. are bigger and stronger than Ndjamas, but the latter breed is persistent to the Tse-Tse fly), animals may suffer from diseases and the feeding condition is extremely important. This latter factor is crucial in semi-arid zones, where draught animals have to do the hardest work at the end of the dry season, when they are in poorest condition.
But even when animals are in a reasonable good condition, the output is small when placed against the requirements set by the soil characteristics. Some data typical for the African situation are given below.

Table 41*. Output of draught animals under African conditions (Munzinger, 1982).*

Team	Live weight (N)	Tractive effort (N)	Working speed (km/h)	Working hours per day (h)
1 donkey	1250	250	2	3 - 3.5
1 horse	3000	350	2.7	5 - 6
1 ox	3500	500	2.4	4 - 6
2 oxen	7000	850	2.3	4 - 6

These data should be compared with draught requirements for tillage operations: tillage with a cultivator of a dry, hardset soil will require at least 2 kN per chisel of approx. 5 cm wide at a working depth of 10 cm. Thus it is clear that the possibilities with ADP are limited to (a) tillage of moist, and thus soft soil, and (b) tillage of dry and hard soil with implements using very narrow working tools (such as tines, rippers).

Training, housing, care. Animals, but also the farmers going to work with ADP need to be trained, during the periods they work extra care and protection is needed and e.g. vaccinations or drugs have to available.

Burden of the farmer. Is heavy during animal draught tillage. It is certainly true that a shift from tillage by hand to tillage using animal draught power is a very big step forward in terms of capacity, timeliness and relative ease of work for the farmer. Still, it is a hard and tedious job to carry out tillage operations on the farm. Ploughing requires that the farmer walks behind the plough, thus travelling approx. 50 km per ha, lifting the implement out of the soil and turning it around roughly 500 times during that same ha, indicating that tillage with animal traction cannot be considered as easy and attractive.

Gender aspects. Almost all households of small farms in Africa are characterized by a strong partition of tasks between the various actors (men, women, children). Often, fields where staple food or cash crops are grown, are managed (soil preparation, planting, harvesting) by the male members of a family, but the weeding is done by women and children. The female family members are responsible for other fields where e.g. vegetables are grown or crops to earn some extra income. When ADP is used or introduced, the handling of the animals is also typically a man's job. This may lead to conflicts when ADP can also be used for weeding (Muylwijk and Smetsers, 1996).

Economics (costs vs. benefits). In subsistence farming situations, the costs of equipment will be prohibitive. Even though the price of a simple mouldboard plough may be no more than 100-140 US$, this is far beyond the reach of the small farmer. The introduction of animal draught equipment usually was tied to the introduction or promotion of cash crops, such as cotton or groundnuts. Recent studies (Williams, 1997) confirm this: introduction of ADP is feasible only in situations (soil and climatic conditions) where higher valued crops can be grown, and where ADP is used for a wide range of activities, including at least ploughing and weeding. Reluctance to using ADP equipment is strengthened by the fact that the sole use of ADP does not guarantee higher yields or better profits. ADP should be accompanied by using fertilizers and/or increased amounts of manure. But even then, yield levels remain unpredictable and influence of factors such as rainfall and pests is very high.
Better incentives for introducing ADP can be found by promoting its use for purposes other than tillage: transport of manure, agricultural produce, water and fuel (wood) can effectively be done using simple ox or donkey carts. Tillage can then be seen as a 'side-effect'. Investments for ADP should be supported by offering credit facilities. Eicher and Baker (1982) hypothesize that introduction of single implements rather than complete packages might be more successful.

In view of above constraints, only a few alternative soil and water conservation techniques for ADP, as listed in 3.2.2. remain.

a. Establishing a (semi)-permanent surface configuration such as a tied-ridging system, which would reduce the need for repeated tillage at the beginning of the season, thereby offering a relatively high resistance against rainwater runoff.
b. Ripping of dry soil (one tine, limited depth, but enough to improve rainwater infiltration and a plant hole for a crop)
c. Using a no-till system with reduced input (hand-planting, and pesticide spraying), mixes of no-till and limited weeding or seedbed preparation.
d. Applying a (semi-permanent) system where non-tilled strips of land act as catchments of water, draining into the areas where crops are grown.

Access to motorised power sources

Not all tractors are suitable in dryland situations under semi-arid climatic conditions, particularly not on problem soils showing crusting and hardsetting behaviour. To fully exploit the advantages of tractors above hand labour or ADP, it should be made possible to carry out tillage operations at the 'dry' side of the workable range. Only then, there is a distinct gain in time and thus the area that can be worked with one tractor. In such situations, however, the tractor has to be able to generate the high draught needed for tilling dry soil, which can easily be a factor 2 to 4 (Wolf and Luth, 1979) higher than for moist soil. This can be achieved only by a combination of sufficient engine power and adequate traction, which results from sufficient weight and tyre shape and size. In practice, 4-wheel tractors of less than approx. 35 kW are too light and not powerful enough to give a reasonable performance on these conditions for conventional tillage (full field ploughing or chiselling).
Adapted types of tillage systems may be applied to reduce the draught requirements and possibly fit these to the available power, making it possible to use either small 4-wheel tractors or 2-wheel walking tractors. The experiences with these tractors on hard and/or loose sandy soils are poor (Holtkamp, 1990) and attempts to introduce these for dryland farming generally have failed, even when acceptable or promising results were obtained during on-station research.

For the vast majority of non-irrigated crop producing regions of West Africa, there is as yet no scope for the introduction or application of tractors for tillage. The constraints mentioned for ADP are even more severe for tractorization, Tractors cannot economically replace hand labour or ADP on any one farm. However, experience in sub-Saharan Africa has also shown that cooperative ownership and management of tractors does not work, neither do government tractor hiring services (Spencer, 1985). One conclusion would then be that improvement of farmers' hand tools and ADP equipment might be the most logical approach.

Yet in view of the apparent difficulties and constraints in the use of draught animals, the motorization aspect should not completely be neglected. In many rural situations the introduction of tractors for farming has led to their use for transport, which is not surprising seen the strong need to carry produce to the market and to transport agricultural inputs, but also goods such as building material to the village. If this 'alternative' use could form an economical basis for the introduction of tractors, then the use on the fields for tillage might form a very useful side-effect.

5.2. Medium and high energy input situations (e.g. Brazil)

In situations where motorised power is available, a much wider offer in tillage systems and technologies for soil and water conservation is available. The final choice by the farmer will, apart from the confidence he has in a certain system, strongly be influenced by practical aspects such as easy access of desired machinery on the market, and by cost-benefit deliberations. Apart from expected crop yield increases resulting from alternative tillage, there are long-term benefits due to e.g. slower soil degradation, lower erosion risk etc. These aspects are not so easy to translate into money flows.

Even when tractors are available to the farmer, this is not (at all) a guarantee that they will be used in an optimum way.

(a) The best farming practices in terms of soil and water conservation effects or efficiency of energy use for a given situation may not be known to the farmers. Possibly there was no experience from alternative methods, no research was carried out to assess other methods, or extension services were not be available to provide the farmers with the necessary information.

(b) Especially there where tractor use is marginally possible, there is often a lack of appropriate equipment or implements which function properly. Examples are the use of ploughs with worn or blunt soil-engaging parts, use of pulled implements where pto driven implements could be used much more effectively.

(c) Ignorance, lack of experience, training or responsibility from the tractor driver may lead to tillage at the wrong moment, at the incorrect depth or with implements which are not properly adjusted, leading to unwanted surface configurations, soil structural damage, excessive energy use etc. This can easily result in an increased risk for runoff and erosion. This problem is often found in situations where the tractor operator is not the farmer, and/or where the farmer is not present on the farm permanently.

Reduced tillage systems with no-tillage as an extreme, show a lower weed control efficiency and therefore rely more on chemicals. The higher management skills required for the conservation tillage systems are commonly recognized.

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SUMMARY

Soil tillage is the manipulation of soil which is generally considered as necessary to obtain optimum growth conditions for a crop. In the same time the resulting modification of soil structure has serious implications for the behaviour of the soil to erosive forces by water and wind. In Chapter 1 an introduction is given to the most important aspects: the objectives of tillage, the conflicting requirements set to tillage, the characteristics of soil and water conservation in the semi-arid tropics, and the nature of tillage research including modelling.

Chapter 2 treats in detail the characteristics of the soils often found in the semi-arid tropics: the SCH soils (sealing, crusting and hardsetting). Sealing and crusting causes problems with emergence of seedlings and with infiltration. The hardsetting soils are difficult to manage, particularly when tillage has to be performed with limited energy inputs. Physical characteristics and low organic matter contents are primarily responsible for SCH behaviour.

In case 1, research undertaken in Mali is reported. Sandy soils of the Sahel area, mainly cropped to millet *(Pennisetum glaucum (L.) R.Br.)* are very sensitive to crust formation. These crusts were found to strongly reduce infiltration capacity. On the typically gently (1-3%) fields runoff is a widespread phenomenon; on the average 25% of the rain (mainly in the form of a few large storms during the rainy season) is lost by runoff. Crust formation and its effect on the infiltration rate was studied in experiments using a rainfall simulator are discussed. On untilled soils the presence of a crust is a permanent feature, and the effect of superficial tillage on crust disturbance disappeared quickly under subsequent rainfall. It was established that rainfall characteristics (aggressiveness, intensity) play a key role in crust formation.

Research reported in case 2 was carried out in Niger. Here, important processes of soil structural changes under rainfall were assessed, to obtain a basis for a proper development of improved soil management methods. Soil and rainfall characteristics of a millet growing area close to Niamey, were determined. Laboratory tests showed a confirmation of what was observed in the field, namely that the coarse sandy soil of the area shows a mechanical behaviour which is extremely dependent on the moisture content at the time of soil handling. Therefore, the workability range is very narrow. Special tillage under wet conditions, resulting in smearing of the surface layer caused a condition which was more resistant to wind erosion. In an extension of the analyses reported in case 1, it was found the rainfall in this region is aggressive; even small storms may fall with high intensities. The major rainfall characteristics of the Sahel differ significantly from those of other semi-arid

areas (such as India). The erratic rainfall pattern in combination with the sandy nature of the soil in the region studied, leads to an extremely small number of days available for planting millet, on average around 11 for the season. Therefore, time-efficiency of soil preparation and planting methods is even more important than a positive effect on SWC and crop emergence aspects.

Chapter 3 gives a review of the various tillage systems as they may be applied for soil and water conservation, based the soil characteristics and on different mechanization levels.

A study carried out in Brazil is presented in case 3. In a highly mechanized farming situation, erosion problems on sloping, red soils in the state of Paraná are high. Conventional tillage is based on the use of heavy disk ploughs and repeated passes with disk harrows in order to prepare a seedbed. This system causes severe erosion damage because of reduced infiltration rates and unstable topsoil. The zero-tillage system is a promising and realistic alternative, but is not suited for all farms in the state (small fields, high capital investment for equipment required, lacking knowledge and experience of farmers). The possibilities for the use of chisel ploughs (as an alternative between these two systems) on wheat stubble in a wheat-soybean rotation were investigated. Experiments showed that, compared to conventional tillage systems with disc implements, chisel ploughing left more plant residue at the surface. Except for the duckfoot type, the chisels were able to penetrate down to the bottom of a compacted layer at 12-20 cm depth. In addition, fuel consumption was significantly lower than disc ploughing and slightly higher than heavy disc harrowing. The capacities of the chisel ploughs were comparable to the heavy disc harrow. On the other hand, weeds and large amounts of straw may cause considerable practical difficulties and require adequately dimensioned chisel ploughs. Thus when applying the alternative tillage, adapted sowing equipment, able to cope with surface residue is required.

In case 4, studies on the agronomic effect of tillage systems fit for animal traction in West Africa are reported. Crop establishment is an important yield factor for pearl millet in the Sahel. Therefore, a series of experiments was conducted to determine the effects of seed size, depth and method of planting, millet variety, tillage, and soil fertilization upon seedling emergence, crop establishment, and yield. All experiments were conducted on a sandy Psammentic Paleustalf in Niger. Three millet varieties were studied, and for all of these, out of a range of sowing depths from 1 to 7 cm, a sowing depth of 3-5 cm resulted in the highest percentage emergence, the highest above-ground biomass, and most secondary roots. High soil temperatures are common during establishment, typical maximum temperatures at a depth of 1 cm exceed 46° C. It was found that the adverse effects of wind erosion and these high temperatures were least when sowing in hills (the traditional hand-method); establishment, crop stand survival, and yield were better under hill planting than drilling seed. Tillage of the field before sowing increased initial stands and their survival, the latter also depending on fertility. Thus, improved crop yields result from better stand survival and higher yields per hill. Fertilizer application (17 kg ha^{-1} P and 40 kg ha^{-1} of N) caused a threefold increase in grain yields. Ridging without prior tillage and ploughing increased grain and stover yields two- to three-fold. In combination with fertilizer application, sixfold yield increases were obtained. In view of the time limitations, ridging without prior tillage was preferable to ploughing, as it is a much faster operation giving equally good results in terms of crop establishment and yield.

Chapter 4 deals with simulation models for soil and water conservation and the difficulties of modelling tillage effects. A review of the most important models currently used in SWC is presented with a brief indication if and how tillage is incorporated in these models. Various options of approaching tillage effects by modelling are given.

In case 5, the development and application of a model simulating the role of tillage in SWC is presented. The data used are mainly from the situation prevailing in the West African Sahel and Sudan zone, characterized by a low input (particular N and P) rainfed farming system, growing cereal crops such as millet. Two types of soil tillage are distinguished: tillage aimed at water conservation (by increasing infiltration and/or surface roughness) and tillage aimed at weed control. Various scenarios are evaluated by combining simulation models for plant production (WOFOST) and soil water movement (SWATRE), developed and adapted for application in these regions. Based on simulations of 35 years of weather data, it was found that water conserving tillage *as such* has a very small yield-conserving effect because of the limitations set by the nutrient status. Elimination by tillage of the competition by weeds had a larger effect on the grain yield of a millet crop.

In case 6, the water balance for millet fields and for permanently crusted natural pastures is described, with special emphasis on the role of the crust in governing infiltration and runoff. This study was based on the same field experiments in Mali as described in case 1. It was tried to quantify the effect of tillage as it destroys the crust and increases the surface storage for rainwater. The crust-breaking effect was found to last for only a few rainshowers, but the increase of surface storage is more permanent. The effect of a tillage system on the water balance of a millet crop was calculated. From this calculation it was concluded that tied ridges, giving a surface storage of 20-30 mm, could completely prevent runoff, compared to about 50% loss under the conventional system. Such a savings would allow earlier sowing and thus prolong the vegetative growth by as much as 20 days, which might increase the average millet yield (500 kg ha^{-1}) by roughly 40%.

In Chapter 5, the prospects for development of tillage systems for the difficult SCH soils are discussed. Analysis of the various options shows that no-tillage is not a solution for the semi-arid tropics with hardsetting soils. It also can be argued that the introduction of animal traction in situations with purely handlabour, in many cases is not feasible, and notwithstanding all other problems, tillage by tractors should be investigated as a serious option.

SAMENVATTING

Grondbewerking is de manipulatie van grond die nodig geacht wordt om optimale groei en ontwikkelingsomstandigheden te bewerkstelligen voor een gewas. Tegelijkertijd heeft de verandering van de bodemstructuur die daar van het gevolg is verstrekkende implicaties voor de reactie van grond op erosieve krachten van water en wind. In hoofdstuk 1 wordt een introductie gegeven ten aanzien van de belangrijkste aspecten van grondbewerking: de beweegredenen, de conflicterende eisen gesteld aan grondbewerking, de karakteristieken van bodem en waterconservering in de semi-aride tropen en de aard van het onderzoek in de grondbewerking en de modellering daarvan.

In hoofdstuk 2 worden de karakteristieken behandeld van de grondtypen die vaak in de semi-aride tropen voorkomen: de zgn. SCH gronden (sealing, crusting en hardsetting), korstvormende gronden en gronden waarvan de bouwvoor tot een hard, massief geheel ineen kan zakken. De korstvormende gronden veroorzaken vooral problemen bij de opkomst van zaailingen en bij water infiltratie. De 'hardsetting' gronden zijn moeilijk te bewerken, met name als er weinig energie voor trekkracht beschikbaar is. Fysische eigenschappen en lage gehaltes aan organische stof zijn in de eerste plaats verantwoordelijk voor deze karakteristieken.

In case 1 wordt verslag gedaan van onderzoek uitgevoerd in Mali. Lichte gronden in de Sahelstreek waar meestal gierst (*Pennisetum glaucum* (L.) R.Br.) wordt geteeld, zijn erg gevoelig voor korstvorming. Deze korsten bleken de infiltratiecapaciteit sterk te verminderen. Vandaar dat op de typisch lichtglooiende velden (1-3%) afstroming een wijdverbreid verschijnsel is. Gemiddeld gaat 25% van de regen (die veelal in de vorm van enkele grote buien valt gedurende het regenseizoen) verloren door afstroming. Deze korstvorming en het effect op de infiltratiesnelheid is bestudeerd in experimenten waarbij een regensimulator werd gebruikt. Op niet bewerkte gronden is de korst permanent aanwezig. Het positieve effect van oppervlakkige grondbewerking om de korst te breken verdween snel bij de volgende buien. De eigenschappen van de regenbuien ("agressiviteit") spelen een belangrijke rol bij korstvorming.

Het onderzoek waarvan verslag wordt gedaan in case 2 werd uitgevoerd in Niger. In dit onderzoek werden veranderingen in bodemstructuur onder regen bestudeerd teneinde een goede basis te verschaffen voor het ontwikkelen van verbeterde grondbewerkingssystemen. Bodem- en regenvaleigenschappen werden bepaald van een streek in de buurt van de hoofdstad Niamey waar veel gierst verbouwd wordt. Laboratorium proeven gaven een bevestiging van wat er in het veld werd waargenomen, namelijk dat de grofzandige bodem een mechanisch gedrag vertoont dat zeer sterk afhankelijk is van het vochtgehalte waarop bewerkt wordt. De bewerkbaarheidsgrenzen liggen daardoor zeer dicht bij elkaar. Een speciale manier van grondbewerking waardoor de oppervlaktelaag versmeerd wordt bleek een goede weerstand van de grond tegen winderosie te bewerkstelligen. Na een uitbreiding van de regenval analyses zoals in case 1 uitgevoerd, bleek inderdaad dat de regenval in deze streek zeer agressief is, zelfs in kleine buien valt de regen met hoge intensiteiten. De belangrijkste regenval eigenschappen van de Sahel zijn significant verschillend van die van andere semi-aride tropische gebieden (zoals bijv. India). Het onvoorspelbare regenvalpatroon, in combinatie met de zandige bodems heeft als resultaat dat het aantal dagen dat beschikbaar is voor het zaaien van gierst, enorm klein is: gemiddeld ongeveer 11 per seizoen. Daarom is onder deze omstandigheden de tijdigheid van de grondbewerkings- en zaaimethoden minstens zo belangrijk als een positief effect op bodem- en waterconservering of opkomst van het gewas.

Hoofdstuk 3 geeft een overzicht van de verschillende grondbewerkingssystemen zoals deze voor bodem- en waterconservering kunnen worden toegepast. Dit overzicht is gebaseerd op zowel bodemeigenschappen als mechanisatieniveaus.
In case 3 wordt onderzoek uit Brazilië besproken. Erosieproblemen op de hellende, rode gronden van de staat Paraná, onder hoog gemechaniseerde landbouw zijn groot. Conventionele grondbewerking is gebaseerd op gebruik van zware schijvenploegen, waarna herhaalde malen met een schijveneg moet worden gewerkt om een acceptabel zaaibed te maken. Dit systeem veroorzaakt een sterk verminderde infiltratie van regenwater en een instabiele oppervlaktelaag, resulterend in grote erosieschade. Zero-tillage (directe inzaai zonder bewerking) is een veelbelovend en haalbaar systeem, maar niet geschikt voor alle bedrijven in de staat (te kleine percelen, veel kapitaal nodig voor werktuigen, ontbrekende kennis en ervaring van de boeren). De mogelijkheden voor het gebruik van cultivatoren (als een alternatief tussen conventioneel en zero-tillage) in een tarwe-soja rotatie werden onderzocht. Proeven met vier verschillende cultivatoren toonden aan dat deze werktuigen meer gewasresten aan het oppervlak achterlaten dan schijvenwerktuigen. De tanden van de cultivatoren (met uitzondering van de platte 'ganzenvoet') konden de verdichte laag op 12-20 cm diepte losbreken. Het brandstofgebruik bij cultivatoren is significant lager dan de schijvenploeg en iets hoger dan de zware schijveneg. De capaciteiten van de cultivatoren waren vergelijkbaar met die van de zware schijveneg. Daar tegenover staat dat onkruid en grote hoeveelheden stro serieuze praktische problemen opleveren en ruim bemeten werktuigen vereisen. Dit impliceert ook dat na bewerking met cultivatoren zaaimachines gebruikt moeten worden die geschikt zijn om in gewasresten te werken.
Proeven uitgevoerd in West Afrika, gericht op het teeltkundig effect van grondbewerkingssystemen voor dierlijke trekkracht worden besproken in case

4. De kwaliteit en mate van opkomst van een gewas is een belangrijke opbrengst factor voor gierst in de Sahel. Een serie proefnemingen werd uitgevoerd teneinde de effecten van zaadgrootte, gierst variëteit, zaaidiepte en -methode, bewerking en bemesting te bepalen op factoren als opkomst, groei en opbrengst. Alle proeven werden uitgevoerd op dezelfde zandgrond (Psammentic Paleustalf) als besproken in case 2. Drie gierst variëteiten werden gebruikt. Bij alle gaf een zaaidiepte van 3 tot 5 cm (uit een reeks van 1 tot 7 cm) de hoogste opkomst, de grootste biomassa van de bovengrondse delen, en de meeste secundaire wortels. Hoge temperaturen zijn veel voorkomend tijdens de begingroei, en kunnen oplopen tot boven de 46° C op 1 cm diepte. Het bleek dat de nadelige effecten van winderosie ('zandstralen') en de hoge temperaturen het minst waren als de gierst op de traditionele manier, dat wil zeggen in 'hills' (clusters van 30-40 zaden) gezaaid werd. Opkomst en overleving was hier beter dan wanneer er in rijen gezaaid was.
Grondbewerking (vergeleken met het direct in 'hills' zaaien) gaf een betere opkomst en overleving, waarbij ook de voorziening van nutriënten belangrijk was. Toediening van kunstmest (17 kg ha^{-1} P en 40 kg ha^{-1} N) gaf een verdrievoudiging van de graanopbrengst. Het maken van ruggen zonder voorafgaande grondbewerking gaf een verdubbeling tot verdrievoudiging van graan en stro opbrengst. In combinatie met kunstmest, kon een zesvoudige verhoging worden behaald. Gezien de korte beschikbare tijd voor bewerken van de grond en de vergelijkbare meeropbrengsten heeft het maken van ruggen de voorkeur boven ploegen.

Hoofdstuk 4 behandelt simulatiemodellen voor bodem- en waterconservering en de problemen om effecten van grondbewerking te modelleren. Een overzicht wordt gegeven van de belangrijkste modellen die op dit moment in bodem- en waterconservering worden gebruik, met daarbij een korte toelichting of, en zo ja hoe grondbewerking in deze modellen verwerkt is. Diverse opties om effecten van grondbewerking in een model te benaderen worden besproken.
De ontwikkeling en toepassing van een model die de rol van grondbewerking in de bodem- en waterconservering kan simuleren, wordt beschreven in case 5. De gebruikte input-gegevens zijn een weergave van de typische omstandigheden van de West Afrikaanse Sahel - Sudan zone: de teelt van graangewassen in een regenafhankelijk systeem een lage input van N en P. In het model worden twee typen grondbewerking onderscheiden, gericht op: (a). bodem- en waterconservering (door het verbeteren van de infiltratie en/of het verhogen van de oppervlakteberging) en (b). onkruidbestrijding. Diverse scenario's werden geëvalueerd door gebruik te maken van het model DUET. Dit model combineert het gewasgroeimodel WOFOST en het bodem-water model SWATRE en werd aangepast om de typische omstandigheden van de semi-aride tropen te kunnen simuleren. Gebruik makend van weersgegevens van 35 jaar bleek dat grondbewerking ter verbetering van waterconservering

op zich een klein opbrengst verhogend effect had gezien de limitaties die door de lage nutriëntenstatus worden veroorzaakt. Het verminderen van de onkruid-concurrentie door grondbewerking had een groter opbrengst-verhogend effect.
In case 6 wordt aandacht besteed aan het bepalen van de waterbalans voor velden waarop gierst wordt verbouwd, en voor natuurlijke weiden met een permanente korst aan het oppervlak. Hierbij wordt bijzondere aandacht gegeven aan de rol van de korst die infiltratie en afstroming beïnvloedt. Deze studie is gebaseerd op de omstandigheden zoals ook in case 1 beschreven. Getracht werd de invloed van grondbewerking (breken van de korst en verhogen van de oppervlakte berging voor regenwater) te kwantificeren. Het korst-brekende effect bleek slechts enkele buien te duren, maar de verhoging van de oppervlakteberging is van langere duur. Het totale effect op de waterbalans van een gierst gewas werd berekend. Hieruit kon worden opgemaakt dat het systeem van 'tied ridges' (verbinden van ruggen met dwarsdammetjes) een oppervlakteberging van 20 tot 30 mm gaf, waardoor afstroming volledig kon worden voorkomen. Het conventionele systeem met niet-verbonden ruggen gaf tot 50% afstromingsverliezen. Een besparing van water van deze orde kan een vervroeging van de zaaidatum mogelijk maken en daardoor de periode van vegetatieve groei met maximaal 20 dagen verlengen. Hierdoor kan de gierstopbrengst met zo'n 40% verhoogd worden.

In hoofdstuk 5, tenslotte, worden een aantal mogelijkheden tot ontwikkeling van grondbewerkingssystemen voor de gronden met problemen als gevolg van korstvorming en 'hardsetting' besproken. Een analyse van de mogelijke opties geeft aan dat zero-tillage geen oplossing is voor de semi-aride tropen met hardsetting gronden. Het kan eveneens beargumenteerd worden dat de introductie van dierlijke trekkracht in situaties waarin nu nog alleen met de hand gewerkt wordt, vaak niet haalbaar is. Vandaar dat grondbewerking met tractoren toch als een serieuze optie moet worden onderzocht, ondanks alle problemen die zich daarbij voordoen.

CURRICULUM VITAE

Willem Bastiaan Hoogmoed was born on the 2nd of January 1949 in Ooltgensplaat, (Goeree-Overflakkee), The Netherlands, and grew up on an arable farm.
After obtaining the diploma "HBS-B" in 1965, he went to the HLS (Agricultural College) in Dordrecht, where he obtained the diploma in 1967. From 1967 to 1974 he studied at Wageningen Agricultural University and obtained his "Ingenieurs" degree in Agricultural Engineering (with majors in Soil Tillage, Mechanization, Irrigation and Soil Physics). During his study he spent time for practical training in Surinam and Australia.

From 1974 to 1976 he was lecturer in Agricultural Engineering at the University of the West Indies, Faculty of Agriculture, (St. Augustine campus, Trinidad and Tobago).

In 1976 he joined the department of Soil Tillage of Wageningen Agricultural University. From 1976 to 1981 he was involved in research carried out in the framework of a cooperative project with the Hebrew University, Rehovot, Israel on the "development of criteria and methods for improving the efficiency of soil management and tillage operations with special reference to arid and semi-arid regions". During that time, research was (apart from activities in Israel) also undertaken in Mali, in cooperation with the project "Production Primaire au Sahel".
In 1981/1982 he spent one year as a consultant to a GTZ funded project on erosion control in Paraná, Brazil.
From 1983 to 1989 research was carried out together with CIRAD (France) in Mali and Burkina Faso in the framework of an EC-funded project "Agregation des sols pauvres en argiles gonflantes au Sahel".
Since 1990 the main focus of his research work is within the Sahel-part of the program "Sustainable land use in the tropics", with activities in Burkina Faso.

Various consultancies were carried out in tillage related projects in India, China, Zambia and Marocco.

At Wageningen University, he is also active in the specialization Tropical Landuse, as study-coordinator.

ABBREVIATIONS and ACRONYMS:

AGNPS	AGricultural NonPoint Source pollution model
ANSWERS	Areal Nonpoint Source Watershed Environmental Response Simulation
APSIM	Agricultural Production Systems Simulator
CREAMS	A field scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems
CropSyst	Cropping Systems Modelling Framework
DNDC	DeNitrification - DeComposition
DSSAT	Decision Support System for Agrotechnology Transfer
ENWATBAL	ENergy and WATer BALance of a sparse crop
EPIC	Erosion/Productivity Impact Calculator
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
GUEST	Griffith University Erosion Sedimentation Template
MUTillS	Melbourne University Tillage Simulator
USLE	Universal Soil Loss Equation
PERFECT	Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques
RUSLE	Revised USLE
SLEMSA	Soil Loss Estimation for Southern Africa
SPAW	Soil-Plant-Air-Water model
SWAT	Soil and Water Assessment Tool
SWIM	Soil Water Infiltration and Movement model
SWRRB	Simulator for Water Resources in Rural Basins
WAVE	A mathematical model for simulating Water and Agrochemicals in the soil and Vadose Environment
WEPP	Water Erosion Prediction Project model

DAS	Days After Sowing
DM	Dry Matter
FYM	Farmyard manure
FC	Field Capacity
GIS	Geographic Information System
SAT	Semi-arid tropics
SCH	Sealing, crusting and hardsetting
SOM	Soil organic matter
SWC	Soil and water conservation

LON	Londrina (Paraná)
VV	Vila Velha (Paraná)