1 The Response of Tilled Soils to Wetting by Rainfall and the Dynamic Character of Soil Erodibility

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INTRODUCTION

If a soil, especially a freshly tilled one, is exposed to rainfall it does not remain unchanged. Interactions between the soil system and rainfall take place, which alter the state of the soil system. This is evident from changes in a number of soil physical properties. Some of these changes are irreversible, and this means that successive rainfall events act upon a soil with different initial hydraulic properties. This leads to different responses of the soil to rainfall, in terms of runoff and erosion, and it may explain the large degree of scatter which often is observed in relationships between rainfall, runoff and erosion.

In this chapter a simple conceptual model of the evolution of a tilled soil in the course of a year is described. The evolution is related to the dynamic character of soil properties which have an influence on infiltration and the generation of overland flow. From the model it will appear that the tilled layer can follow evolutionary pathways which may differ from year to year, depending on the pattern of rainfall. The model is still provisional, as it is based on ongoing field and laboratory work, which was started in 1983. A main fieldwork area is Dutch South-Limbourg, which is part of the West European loess belt.

A central notion in the evolution of a tilled soil is the 'response to wetting'. This term was introduced by Imeson and Verstraten (1986) to include the various reactions of a soil when it is exposed to wetting by rainfall, with or without the effect of raindrop impact. It may be useful to make a distinction between

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(a) surface response to wetting and (b) subsurface or internal response. The response to wetting of a soil includes processes such as compaction, shrinking and swelling, mellowing, slaking and dispersion. A typical surface response is crusting or sealing. These processes are well described in the literature (Baver *et al.*, 1972; Callebaut *et al.*, 1985; Edwards and Bremner, 1967; Emerson, 1959, 1983; Utomo and Dexter, 1982).

All processes mentioned have an influence on soil porosity, and thus on soil hydraulic properties, such as saturated and unsaturated hydraulic conductivity, water-retention characteristics, sorptivity, time to ponding at a given rainfall intensity and infiltration capacity.

Other soil properties which are influenced by the response to wetting of a soil are bulk density, surface roughness, resistance to penetration and mechanical resistance of the soil surface to detachment by drop impact and/or overland flow.

An important control of the way(s) in which a soil responds to wetting is the stability in water of the structural elements of the soil. These elements may be either naturally formed (peds) or artificially created by tillage (clods). Aggregate stability, as it is generally termed, depends on the presence and proportion of various soil constituents (e.g. clay, organic matter) and on the mode of formation of the aggregates (a) by biotic action or (b) by physical or mechanical processes, such as freezing, shrinking or tillage. Biotic processes produce a granulation structure, such as is found in the topsoil of forest soils and under grass. The crumbs or granules are relatively stable in water. Physical and mechanical processes result in a fragmentation structure, the elements of which are relatively unstable in water. Aggregate stability changes with soil moisture content (Hofman and de Leenheer, 1975) and exhibits seasonal variations.

THE EVOLUTION OF A TILLED SOIL UNDER RAINFALL

A loess soil, such as occurs in north-west Europe, is taken as an example of the soils to which the model applies. The model also relates to soils with a 'duplex' character, i.e. those with a sharp texture contrast between topsoil (poor in clay) and subsoil (rich in clay). Characteristics of these soils are a low clay content, a high silt content and a low aggregate stability of the Ap horizon (tilled layer). A freshly tilled condition is taken as a starting point for the description of the evolution of the soil.

For convenience, three periods are distinguished in the evolution of the tilled layer, which correspond with three stages in its development. A comparable subdivision was made by Boiffin (1984) for the evolution of the soil surface. The three periods are: (A) a short period with freshly tilled soil; (B) a period in which rainfall-induced processes lead to a stepwise degradation of soil structure and a stepwise decline of various soil physical properties; and (C) a period in

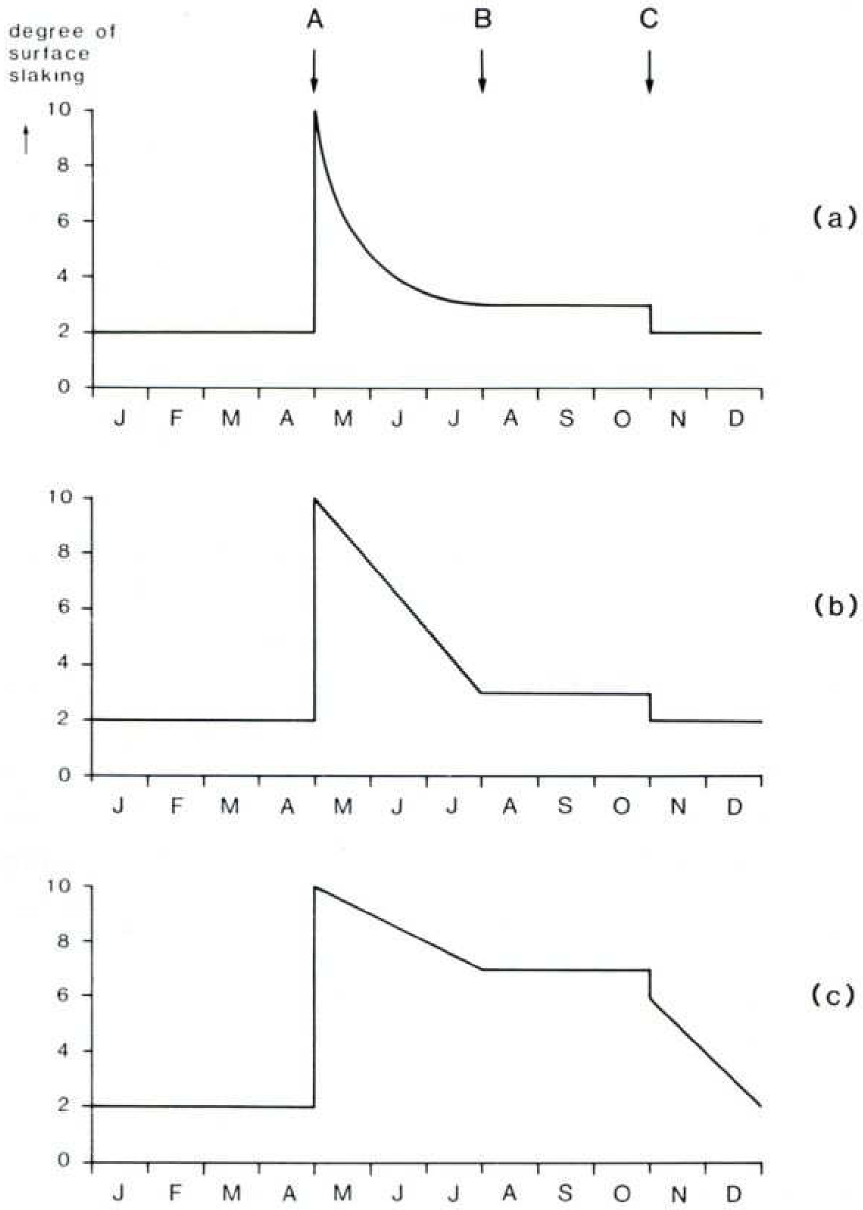

Figure 1.1 Schematic representation of decline of structural status of tilled layer under corn. A, B and C denote times of tillage, 100 per cent crop cover and harvest. (a) Rapid decline by heavy rains in May; (b) gradual decline by continued wet weather in May–July; (c) incomplete decline during dry weather in May–July and continued decline after harvest

which a continuous crust is present at the soil surface and in which no further changes of soil physical properties take place except by biological activity. Schematic illustrations of the evolution of the tilled layer are given in Figures 1.1 and 1.2.

Period A

Period A immediately follows tillage. This may be either autumn or spring tillage. Various tillage actions may be applied, with various tillage objectives

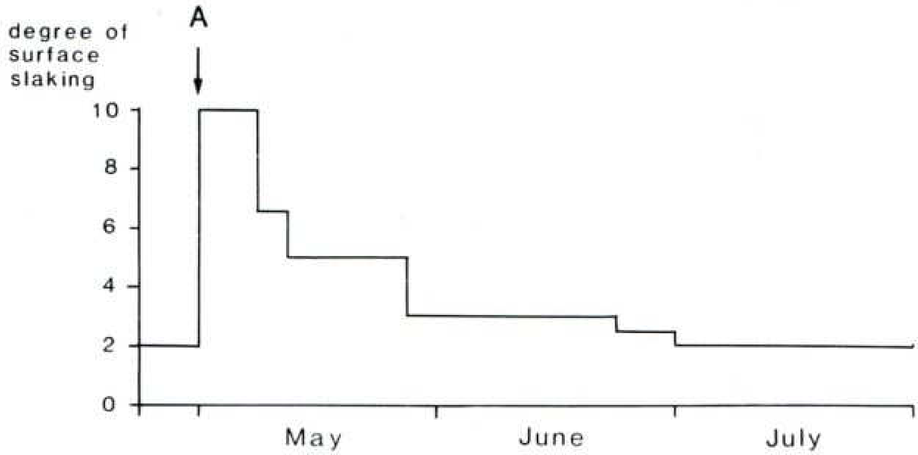

Figure 1.2 Schematic representation of stepwise decline of structural status of tilled layer under corn caused by discrete rainfall events: A denotes time of tillage

and tillage tools, such as ploughing, harrowing, chiselling, disking, rolling and hoeing. Tillage depth may vary. Soil moisture content at the time of tillage influences the results which are attained. It must not be too high, or puddling will occur, nor should it be too low, or tillage will have no effect at all or produce dust. A relatively small range of soil moisture contents remains for the farmer to choose from. However, soil moisture contents at the time of tillage may vary slightly from year to year. This can cause appreciable differences in results of the same tillage operation (e.g. in size of clods). This is a difficulty in obtaining reproducible conditions on runoff plots from year to year.

The effect of primary tillage (ploughing) on the soil is the formation of a fragmentation structure with relatively coarse clods which are loosely packed. Often it is desirable to reduce the size of the clods in the upper part of the tilled layer before seeding (seedbed preparation). This is done by a secondary tillage operation (harrowing), which may be followed by rolling to achieve a certain degree of compaction of the seedbed.

The size of the clods which lie at the soil surface after tillage determines the random roughness of the soil surface. Roughness increases with clod size. Random roughness determines the storage capacity of the soil surface for rainwater. It also influences the velocity of overland flow by exerting a friction resistance on that flow.

The coarser the clods are at the soil surface, the longer it takes before they are broken down under rainfall, other things being equal. The clods of a freshly tilled soil are generally loosely packed with large voids between them. Interped macroporosity is high, bulk density is low, resistance to penetration is low and saturated hydraulic conductivity is high, due to the presence of a system of interconnected macropores. The macropores drain at relatively low suctions and this causes a large decrease in hydraulic conductivity if the soil water suction rises above zero, i.e. if the soil becomes unsaturated (Klute, 1982). Unsaturated flow takes place in the matrix of the clods through the intraped pores, and water under suction will only flow from one clod to another at the points of contact between adjacent clods. In a freshly tilled soil the total contact area between clods will be relatively small, and this explains the low unsaturated hydraulic conductivity of such a soil.

Infiltration capacity (i.e. maximum rate of infiltration of rainwater) will be high in period A. This is due to the presence of macropores which are open to the soil surface (Edwards, 1982). At high rainfall intensities water falling on clods will first be taken up by the clods, but sorptivity decreases and soon rainfall intensity exceeds the infiltration capacity of the clods. Water accumulates on the clod surfaces and flows off them into the macropores between the clods, where it flows down the walls of the pores as free water. This flow of water in macropores is known as bypass flow or short circuiting, as the matrix of the soil is bypassed by the water (Bouma *et al.*, 1977; Beven and Germann, 1982). Macropores also provide important pathways for the escape of air during infiltration of rainwater. Roughness elements protruding above the general soil surface may act as vents for the escaping air (Dixon and Peterson, 1971).

The contact between the tilled layer and the untilled soil underlying it is abrupt. A plough pan or plough sole may be present there. There is a sudden change in many physical soil properties at the plane of contact between the tilled and the untilled soil and this strongly influences the movement of water from the tilled layer into the underlying soil. Percolation is slowed down and this may give rise to the development of a perched water table in the tilled layer and to lateral subsurface flow of water (interflow, throughflow). When and where a perched water table reaches the soil surface, saturated overland flow occurs.

Period A generally does not last very long, depending on the timing of rainfall after tillage. Immediately after tillage the tilled layer begins to settle and to subside under its own weight. Due to this compaction, bulk density increases, porosity decreases and the soil surface sinks. More significant changes take place with the onset of rainfall.

Period B

During period B compaction and subsidence of the tilled layer continues, aided by the impact force of falling raindrops. The most important changes, however, take place at the soil surface. During rainfall the clods and peds, which are exposed at the soil surface, start to break down. Fine material is released, which fills the depressions between the clods and blocks the entrances of the macropores between them. Clods are reduced in size and lose their identity by a process of fusion with neighbouring clods. Remaining parts of clods are immersed in a mass of fine soil material. Random roughness decreases and the soil surface takes on a closed appearance.

The degradation of the soil surface takes place in a stepwise manner, each period of breakdown of the soil structure being triggered by rainfall. Intervals between rainfall events will vary in length, and this leaves the soil in different initial conditions, regarding soil moisture content and aggregate stability, before the start of a rainfall event.

The processes which cause the breakdown of peds and clods at the soil surface are slaking and dispersion. Slaking is the disintegration of structural elements into micro-aggregates and skeleton grains (Edwards and Bremner, 1967). Slaking of initially dry aggregates is ascribed to rapid wetting, causing compression of entrapped air in the aggregates to the point of the aggregate's explosion, when the pressure of the air exceeds the cohesion of the aggregate (Baver *et al.*, 1972). The aggregate may be weakened by stresses, set up by unequal swelling of different parts, when water is rapidly taken up by it. Slow wetting of dry aggregates does not produce the explosion effect. Slaking of initially wet aggregates is caused by raindrop impact. There is evidence (McCalla, 1944) that raindrop impact is not instrumental in the breakdown of dry aggregates. Increasing fall heights of raindrops did not increase the rate of breakdown of initially dry aggreates. Farres (1978), however, works on the assumption that aggregates do not spontaneously break down under addition of water. He observed that they remained intact until raindrop impact accompanied the addition of water. Broken-down aggregates were only found by Farres (1978) at the soil surface and not below the surface crust. Once a crust has developed, it protects aggregates below the surface from the impact of raindrops, thus preventing aggregate breakdown below the surface (Farres, 1978). De Ploey and Mücher (1981) describe unstable loamy soils with a low internal stability of the clods. Under simulated rainfall the clods of the unstable soils (field behaviour) showed the collapse of microstructures and liquefaction of the matrix with a strong reduction of the number of originally present pores (observations in thin sections). It is not explicitly stated by De Ploey and Mücher (1981) whether the collapse of the clods of the unstable soils is due to wetting, to raindrop impact or to the combined effect of wetting and raindrop impact.

Dispersion affects the clay which is present in soil aggregates. Clay domains are broken up and primary clay particles are suspended in the soil solution. If this happens, aggregates fall apart. Dispersion of clay is controlled by chemical conditions in the soil. It occurs when sodium is present as an exchangeable cation above a certain threshold concentration and when the electrolyte concentration of the soil solution is not too high (Agassi *et al.*, 1981), and is often observed under semi-arid climatic conditions. According to Emerson (1983) not only sodium-containing soil aggregates will disperse when immersed in water but also wet soil aggregates with divalent ions only. This occurs after mechanical reworking (remoulding, shearing) of the soils containing divalent ions. This is called mechanical dispersion. In Dutch South-Limbourg there is evidence of dispersion during the winter months. The runoff water in the storage tanks of runoff plots remains turbid during winter whereas sediment in the runoff water settles rapidly during summer.

In the course of period B a layer of fine fragments of aggregates and primary silt and sand-sized particles is formed at the soil surface as a consequence of advanced aggregate breakdown. The particles of this layer are closely packed by the beating action of the falling raindrops and form a crust. On top of this slaking crust thin layers of fine sediment may be deposited by overland flow.

Crust formation may take place in winter (after autumn tillage) or in summer (after spring tillage). It may be caused by high- or low-intensity rainfalls and may be due to breakdown of initially dry or initially wet aggregates. These different conditions of crust formation are reflected in the physical properties of the crust (Römkens *et al.*, 1985).

The alteration in the state of the soil surface during period B greatly affects a number of soil physical properties, such as infiltration capacity, random roughness of the soil surface and mechanical resistance of the soil surface to detachment by drop impact and flowing water. The decrease in porosity and change in pore-size distribution of the tilled layer affect bulk density, penetration resistance, saturated and unsaturated hydraulic conductivity and water-retention function. Some results of measurements of these properties will be presented in the next section.

As mentioned above, the pathway of the evolution of a tilled soil during period B, and the duration of period B, may differ from year to year, according to differences in the pattern of rainfall. In Figure 1.1 three evolutionary pathways are sketched for the same soil, following ploughing in the spring. In Figure 1.1(a) a high-intensity thunderstorm falls on a dry soil in April or May. This causes a strong response from the soil. Extreme slaking occurs and overland flow takes place with deposition of sediment. In case (b) the soil remains wet during the spring and early summer by frequent and prolonged rainy periods. Slaking takes place slowly and gradually, and no sedimentary crust is formed. In case (c) a dry spring and early summer is followed by a rainy August and September. No appreciable degradation of soil structure occurs, at first by the lack of rainfall and later by the protection of the soil surface by the fully developed crop.

Some recovery of roughness, porosity and infiltration capacity may take place during the growing season due to biological activity in the soil (e.g. by earthworms). From studies on untilled soils it is known that macropores formed by earthworms and crop roots contribute to the relatively high infiltration capacity and hydraulic conductivity of these soils (Edwards *et al.*, 1988).

Period C

During period C no further changes of the tilled layer and its physical properties take place. Crusting of the soil surface and compaction and subsidence of the tilled layer are at a maximum. This condition is illustrated by the stubble field, which remains after the harvest of corn in autumn. Period C extends from midsummer all through autumn and winter until the spring of the next year if no tillage is carried out after harvest and/or no winter crop is sown. This can cause appreciable runoff during winter from rain as well as from melting snow. Runoff coefficients of 100 per cent have been measured on runoff plots in South Limbourg during some wet winter months on corn stubble fields. In fact, winter runoff amounts were observed to be much higher than summer runoff if period C lasted throughout the winter.

FLUCTUATIONS IN SOIL PROPERTIES RELATED TO SOIL ERODIBILITY DURING THE YEAR

To illustrate the conceptual model of the evolution of a tilled soil outlined above, some results of measurements of a number of soil physical properties during the year will be presented. Continuous records of changes at one site are not yet available as the work is still continuing.

The degree of surface slaking can be assessed by visual observation and expressed on a scale of 1 to 10. A freshly tilled soil is rated with 10 and a completely crusted surface has a rating of 1. To obtain reproducible results by different observers, field soils are compared with a series of reference photographs (Boekel, 1973). Degree of slaking can be related to rainfall amount and intensity, and can be used to rapidly evaluate the effect of different tillage systems on the response to wetting of a given soil. An example is given in Table 1.1 (Van Mulligen, 1988).

Surface roughness changes can be evaluated with a chain of standard length, which is laid out on the soil surface in such a way that it follows the microrelief

Table 1.1 Evolution of surface slaking of a tilled loess soil. Evolution of surface slaking under different cropping systems of corn on a loess soil in Dutch South-Limbourg (Van Mulligen, 1988). Slaking is rated on a scale of 1–10 by comparison with 10 reference photographs; 10 is freshly tilled soil (Van Boekel, 1973). Cropping systems are: (A) Tillage in October; winter rye from October to April, killed by spraying; corn sown between residue of winter rye in untilled soil; harvest of corn in October. (B) Tillage in October; tilled fallow from October to March; tillage in March; summer barley in March–April, killed by spraying; corn sown in barley seedbed; harvest of corn in October. (C) Corn stubble field from October to April; tillage in April; corn from April to October, (C′) Bare fallow all year, tilled in April (reference condition)

		Degree of slaking			
Cropping system	Date of last tillage	28 April 1988	19 May 1988	10 June 1988	24 June 1988
A	30 October 1987	3	4	4	2
B	5 April 1988	9	9	9	4
C	4 May 1988	4	7	7	3
C′	4 May 1988	4	7	7	3

Table 1.2 Changes in bulk density and total pore volume of a tilled loess soil. Bulk density and pore volume of tilled layer of some loess soils in Dutch South-Limbourg (Tiktak, 1983)

	28 March 1983		17 April 1983		5 May 1983		11 July 1983	
	Bulk density (kg m^{-3})	Pore volume (%)	Bulk density (kg m^{-3})	Pore volume (%)	Bulk density (kg m^{-3})	Pore volume (%)	Bulk density (kg m^{-3})	Pore volume (%)
Site 3	1.293	50.4	1.397	46.5	1.401	46.3	1.416	45.7
Site 4	1.160	55.6	1.430	45.2	1.486	43.1	1.371	47.5
Site 5a	1.182	54.7	1.480	43.3	1.507	42.3	1.421	45.6
Site 5b	1.205	53.8	1.460	44.0	1.577	39.6	1.423	45.5
Site 6a	1.243	52.4	1.480	43.3	1.605	38.5	1.481	43.3
Site 6b	1.246	52.3	1.630	37.5	1.537	41.1	1.311	49.8

as closely as possible. A ratio is calculated between the length of the chain and the distance between the two ends of it when it is laid out on the soil surface. A ratio of 1 is found for a completely even soil surface. In Figure 1.3 results are presented of measurements under different cropping systems of corn in South-Limbourg (De Hoog, 1988). Data on bulk density and total pore volume of some loess soils in Dutch South-Limbourg are given in Table 1.2 (Tiktak, 1983). Changes in pore size distribution can be evaluated from soil moisture characteristics by comparing water-retention curves of a given soil on different dates during the growing season (Hill *et al.*, 1985). Curves are given in Figure 1.4 of an autumn-tilled soil. Sampling dates are 28 March and 5 May.

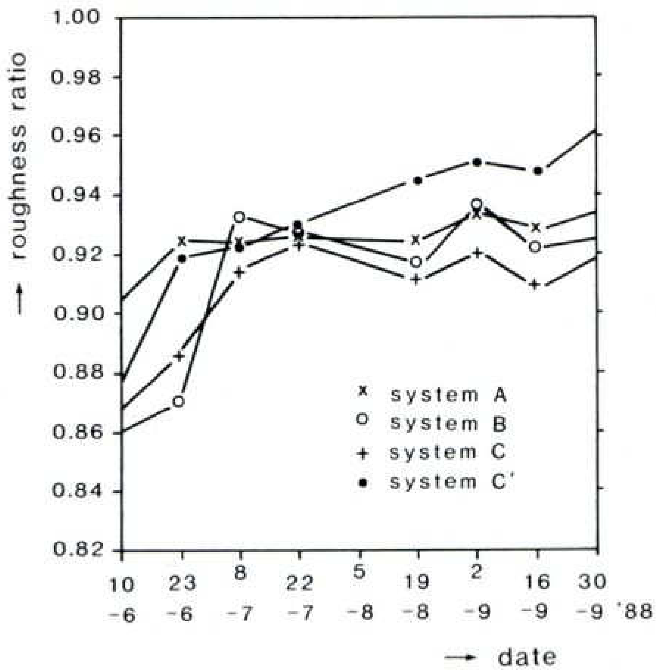

Figure 1.3 Decline of random roughness of soil surface of a loess soil under different cropping systems of corn (De Hoog, 1988). For a description of the cropping systems see Table 1.1

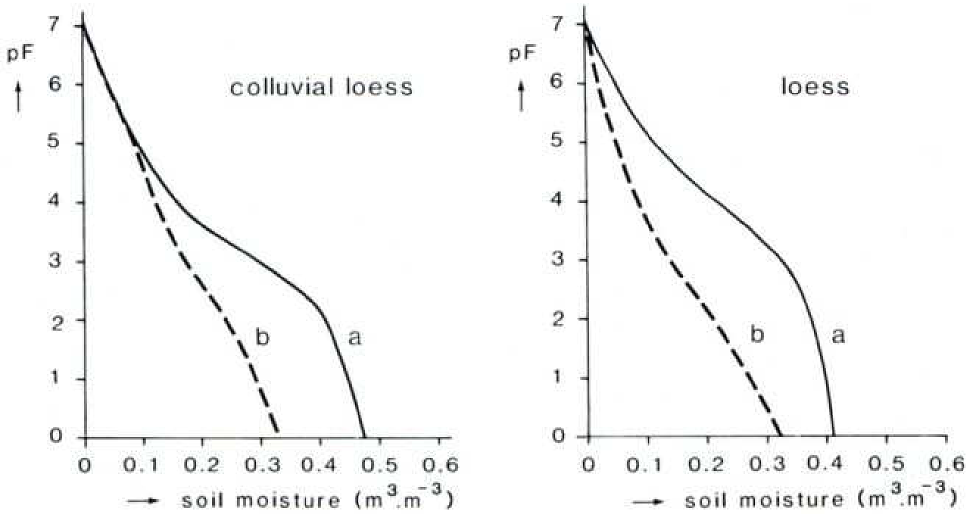

Figure 1.4 Shift of pF curves of tilled layer of autumn-tilled loess soils in Dutch South-Limbourg between 28 March 1983 (curve a) and 5 May 1983 (curve b) (Tiktak, 1983)

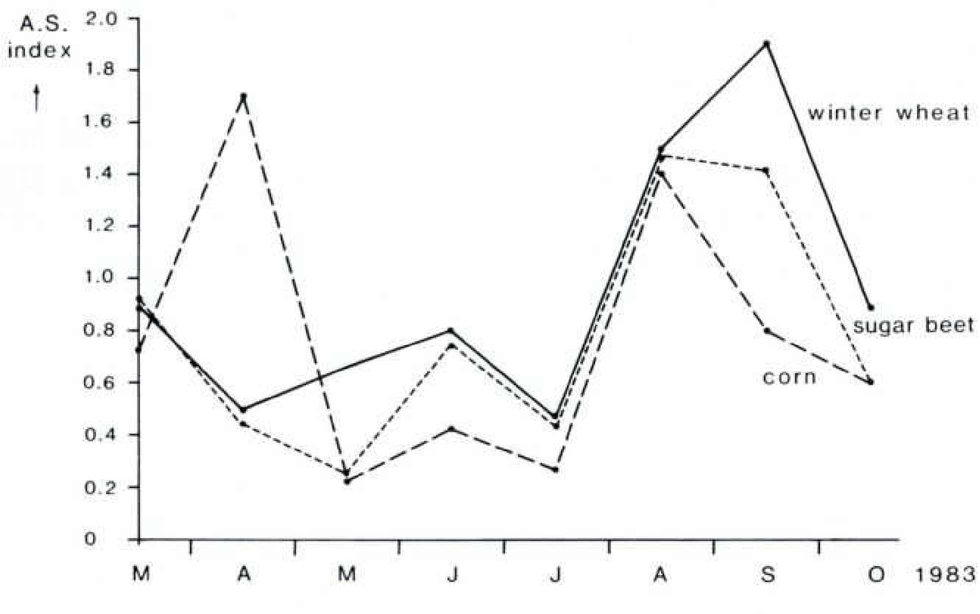

Figure 1.5 Aggregate stability changes under different crops on a loess soil in Dutch South-Limbourg (Van Eijsden, 1986). The aggregate stability index is based on the drop test (Low, 1954)

The curves show a lower moisture content at all suction values on 5 May than on 28 March. This means a reduction in the volume of pores of all size classes between 28 March and 5 May, which must be due to compaction and subsidence of the tilled layer (Tiktak, 1983). Fluctuations in aggregate stability during the growing season under different crops are shown in Figure 1.5 (Van Eijsden, 1986), and the pattern is rather complex. Generally speaking, aggregate stability seems to be at a low in May–June–July and at a high in August–September. This may be related to bacterial activity in the soil.

CONCLUSION

It is clear that soil erodibility, which is controlled by a number of soil physical properties, is far from constant on tilled land during the year. There is a need for a more systematic study of the changes which take place during the year and which, of course, are known in a qualitative way to farmers all over the world. Changes in soil physical properties must be related to the processes which take place in tilled soils and to the specific conditions of soil, weather, tillage system, crop and crop management under which the changes take place.

The dynamic character of soil physical properties, which control runoff and soil loss from agricultural land, must be given full consideration in event-based models of runoff and erosion. Soil erodibility cannot be represented in such models by long-term indices, such as the *K*-factor of the Universal Soil Loss Equation (Römkens, 1985). At present, the *K*-factor is used in the ANSWERS model for soil-loss predictions of discrete rainfall events.

Soil-erosion control will also benefit from a greater knowledge of the magnitude of the changes in soil properties in the course of a year and timing of control measures (e.g. tillage operation) will thus be improved.

An improved knowledge of the hydraulic characteristics and of water movement in the tilled layer may lead to an understanding of the threshold conditions for the initiation of rills. Such initiation by shallow subsurface flow through macropores in the tilled layer (micropipe flow) and the possibility of breakdown of clods and peds by wetting of the tilled layer below the soil surface (i.e. outside the reach of raindrop impact) are underresearched areas at present.

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