Soil Surface Roughness and Infiltration in the Savanna Ecosystem and its Impact on Erosion

Anita Folly

Abstract

This study conducted during the 1994 rainy season describes soil surface roughness and infiltration characteristics of four different soils (Leptosol, Plinthosol, Vertisol and Luvisol/Lixisol) within the savanna ecosystem in the Upper East Region, Ghana. The paper discusses the significance of the various soil types with respect to erosion, being one of the major problems in the region. Infiltration was measured using a Hang double ring infiltrometer and a simple reliefmeter was used for the microtopographical measurements. Various types of soil surface roughness were described using two different indices and the maximum depression storage was calculated. It was shown that the soil type influences infiltration whereas roughness and depression storage are related to soil management-/crops. Management using a hoe as opposed to bullock ploughing seemed most effective regarding increasing roughness/depression storage. In general roughness has little impact when it comes to reducing runoff during high intensity rainfall unless conservation measures are being used. Microtopographical characteristics combined with the relatively low infiltration rates in this ecosystem therefore cause soil erosion.

Keywords

Ghana, erosion, surface roughness, savanna ecosystem, infiltration measurements, microtopography.

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Water deficiency and insufficient nutrients in the soil are the major limiting factors for crop production in the savanna ecosystem. In the Sub-sahelian zone of West Africa where erosion is prevalent even on gently sloping land, the management of water becomes absolutely essential. It is therefore of primary importance to describe as well as analyse the hydrological characteristics such as surface roughness and infiltration in this environment to be able to find optimal tillage and farming methods.

Studies of infiltration and microtopographical characteristics of the soil surface in West Africa have so far primarily been carried out in the Sahelian zone (Hoogmoed & Stroosnijder 1984; Stroosnijder & Hoogmoed 1984; Casenave & Valentin 1989; Valentin 1991). All studies have emphasized the importance of crusting facilitated by a combination of the soil structure, high rainfall intensity and the lack of vegetative cover during those parts of the year when rainfall is high.

Crusting and depression storage determined by the microtopography of the surface are the major parameters determining runoff generation in the savanna ecosystem although infiltration is considered of significance as well. Detailed studies of surface crusting require micro-morphological studies or measurements of the hydraulic conductivity, which are often rather time-consuming and expensive. When examining micro-topographical characteristics, on the other hand, many a variety of methods can be used. The simplest method measures the length of a chain spread out on the soil surface, whereas more advanced techniques use lasers and measurements take place on a grid-basis (Currence & Lovely 1970; Bertuzzi et al. 1990; Edwards 1991; Gascuel-Odoux 1991; Bergsma 1992; Mwendera & Feyen 1992; Schjønning 1994; Bertuzzi et al. 1995; Jensen 1995). Most of the time, roughness indices are derived from these micro-topographical measurements. These indices are, however, not able to describe the dynamics of the microrelief related to crusting or to clarify the influence of crusting on depressional storage capacity (Boiffin 1986). Nevertheless, they do give a good indication of the nature of the surface.

Roughness can be classified as either oriented or random roughness of which oriented roughness is a result of tillage tool marks or general slope effects whereas random roughness is caused by the random occurrence of peaks and depressions resulting from soil clods and organization of aggregates (Bertuzzi et al. 1990). Many indices have been suggested to describe the two types of roughness of which estimates of the standard deviation of height measurements or a related index is the most common (Linden and Van Doren 1986; Bertuzzi et al. 1990). For an estimation of depression storage the total volume of all surface depressions needs to be assessed.

Very little work has been done on factors influencing depression storage on highly erodible soils with silty and/or sandy texture (Edwards 1991), being characteristic of semi-arid environments. The aim of this paper is to describe the surface roughness and infiltration characteristics of four different soils in the savanna ecosystem, Northern Ghana. The study assesses infiltration, roughness and depression storage under different soil managements and discusses their importance with respect to erosion.

The Study Area

The study area, comprising part of two districts around the Bolgatanga township, (figure 1) is characterized by an average rainfall of about 1050mm a year but with big annual variations in both the total amount and distribution.

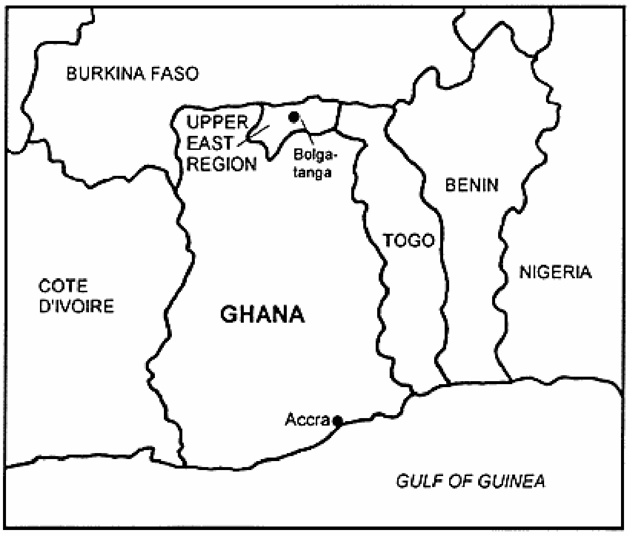

Figure 1: Location of the study area.

The majority of the precipitation falls between May and September (Ghana Meteorological Services 1996).

Four different soil types according to FAO (1990a) are dominant in the study area being Luvisols/Lixisols, Leptosols, Vertisols and Plinthosols (Asiamah 1992). The upland soils are developed mainly from granites. They are shallow, low in inherent soil fertility and have a weak structure with a low organic matter content due to a combination of soil tillage and complete removal or burning of the crop residues. This gives the soils a high susceptibility to erosion (Folly 1995). Other soils in the study area have primarily developed from Voltaian sedimentary rocks (IFAD 1990).

The area falls within the Guinea savanna zone with land use comprising mainly of compound farming areas, bush fields, pasture, fallow and natural wood savanna woodland (IFAD 1990). Major crops are millet, sorghum and groundnuts followed by maize, bambarra beans, cowpeas and tobacco often intercropped. Tillage is carried out with the local hoe and through bullock ploughing depending on the location of the fields and the wealth of the farmer.

Methodology

Rainfall was recorded for almost 1½ months every five minutes using a Campbell Scientific CR10 data logger and a tipping bucket rain gauge.

A representative site was chosen for each of the soil types found within the study area based on available soil maps (Adu 1969; Asiamah 1992) and reconnaissance surveys in the field. The soil maps provided fairly detailed information on soil profile characteristics which is the reason why one test site was considered representative for each soil type. At each site a soil profile was dug and described according to FAO guidelines (1990b). Soil profiles were on the other hand not classified due to lack of sufficient data. Soil names being used to characterize the test sites therefore refer to overall label given on the soil map (Asiamah 1992).

Infiltration rate measurements were carried out (four to five replicates depending upon the uniformity of the measurements) using a Hang double ring infiltrometer as originally described by Bork (1983) and Bork and Rohdenburg (1984), but later modified by Christiansen (1994). This infiltrometer enables measurements on sloping land and uses much less water than the ordinary double ring-infiltrometer, an important parameter in the study area where access to water is difficult.

Finally, the microtopography was measured in two different fields at each test site characterized by different crops and soil management. Microtopographical measurements were carried out inserting a 58 cm by 58 cm metal frame into the soil on which a reliefmeter made out of plexiglass and bicycle spokes with a spacing of 1 cm could be mounted. Recordings were made every 2 cm by drawing the surface of the soil reflected in the heights of the released spokes onto the surface on a piece of paper placed between the plexiglass and the spokes. Point elevation data were derived from readings and surface roughness described using two indices:

1. Random Roughness Coefficient (RRC)
being the standard deviation of elevation points that have been smoothed to eliminate external effects on relief such as slope and tillage tool marks (Currence & Lovely 1970; Helming et al. 1993).

$$RRC=[\frac{1}{N-1}(\sum z'^{2}_{xy}-\frac{1}{N}(\sum z'_{xy})^2]^{1/2}$$

where:

$$z'_{xy}=z_{xy}-(\frac{\sum z^{xy(r)}}{N_{(r)}}-\frac{\sum z^{xy}}{N_{(t)}})-(\frac{\sum z^{xy(c)}}{N_{(c)}}-\frac{\sum z^{xy}}{N_{(t)}})-\frac{\sum z^{xy}}{N_{(t)}}$$

z_{xy} = elevation point — c = column
z'_{xy} = corrected elevation point — t = total
N = total number of values in the data set — r = row

2. Multiple Regression Index (MRI)
A plane of best fit is calculated for each test site using linear multiple regression with row and column positions as independent variables and height readings as dependent variable. The index becomes the standard deviation of the height residuals calculated as the difference between the height readings and the plane. This index includes tool marks and also general slope effects and is therefore suitable for studies relating to soil erosion, surface water storage, the infiltration rate etc. (Currence & Lovely 1970).

To get information on depression storage, MAXimum Depression Storage (MAX DS) was determined using the formula:

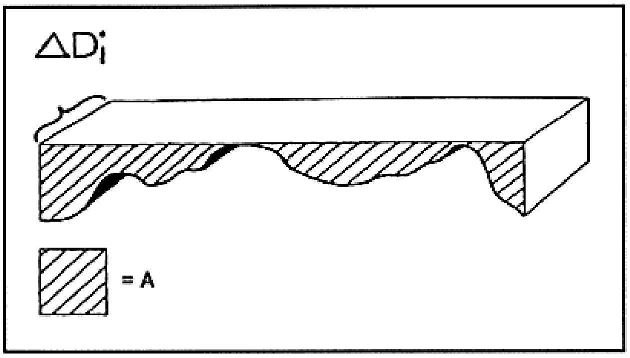

Figure 2: Parameters used to determine maximum depression storage.

$$MAX\ DS=\sum_{i=1}^{n} A_i \times \Delta d_i$$

where:
Δd_i = the distance between two micromorphological measurements (in this case 2 cm).
A = area below the highest elevation point in each row, determined by planimetration (figure 2).

Results and Discussion

The general description of the test sites (table 1) reflects the relationship between crops and soil management observed in the study area. For example, groundnuts are generally found on bullock-ploughed fields whereas fields with rice are managed with a hoe. Most millet and sorghum fields were managed with a hoe as well.

In the following a brief description of the various hydrologic characteristics will take place.

Rainfall Characteristics

A total of 332.5 mm was recorded in the period 27 June to 9 August 1994 with daily rainfall varying from 0 to 61 mm (fig. 3). Within the northern regions of Ghana a total daily rainfall of close to 100 mm a day occurs almost every year though the annual mean rainfall for the study area has been 40.04 mm with a standard deviation of 6.33 (Tandoh 1973; Kasei 1989). Drought was prevalent at the beginning of the season causing crop failures almost over the whole region.

Table 1: General description of the test sites.

Location	*Soil type*	*Test Site no*	*Soil Management*	*Crops**	*General remarks*
Gani	Plinthosol	1	Hoe	Rice	
		1A	Hoe	Sorghum/okro	
Zanlerigu	Vertisol	2	Hoe	Sorghum/okro	Recently weeded.
		2A	Bullock/hoe	Groundnut	First bullock ploughed, later weeding with hoe
Damolgzo	Luvisol/Lixisol	3	Hoe	Late millet	Recently reshaped with a hoe
		3A	Bullock	Groundnut	
Yakoti	Leptosol	4	Hoe	Early millet	Due to drought, field is partly bare.
		4A	Hoe	Early millet/okro	Recently weeded.

** at time of experiment*

Rainfall intensities varied a lot throughout the period with a maximum intensity of 124.5 mm/hr. Intensities were not exceptionally high compared with the previous years where rainfall intensities reaching 230 mm/hr had been observed. Measured intensities are significant on the other hand and may therefore cause erosion.

Infiltration of the various Soil Types

The smoothed infiltration curves for the four soil types being tested (figure 4) show overall low infiltration rates. The lowest infiltration rate is observed for the Leptosol getting close to zero 35 minutes after the onset of the experiment. The relatively shallow depth of the topsoil (10 cm) demarcated by an impenetrable layer consisting of

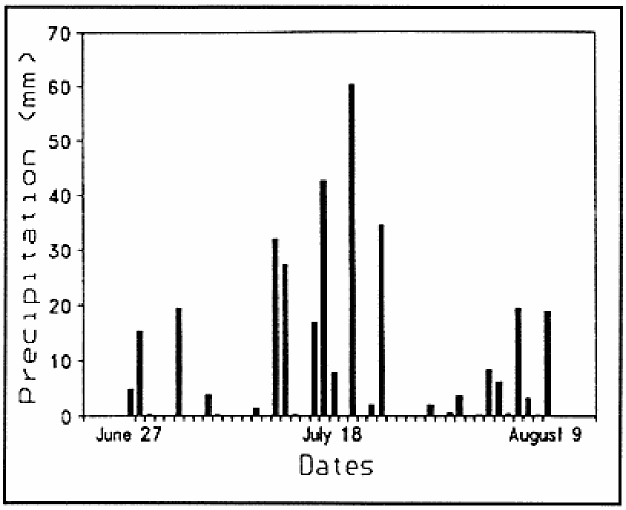

Figure 3: Rainfall characteristics in the period 27 June to 9 August 1994.

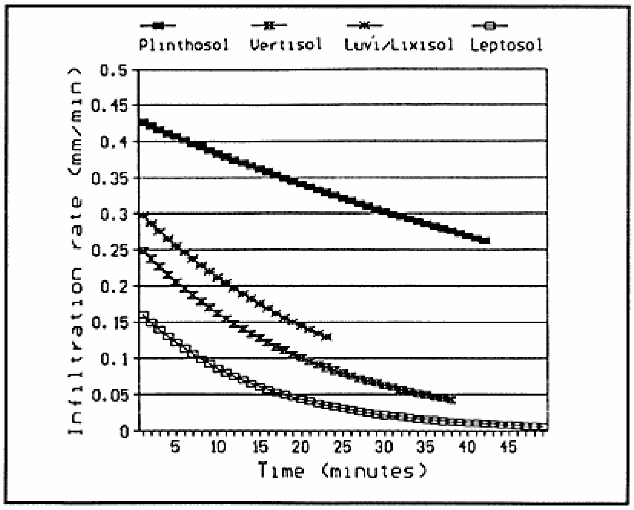

Figure 4: Smoothed infiltration curves for the four soil types.

highly weathered and disintegrated rock seemed to cause the low infiltration rate.

A slightly higher infiltration rate was observed for the Vertisol being governed primarily by the textural composition of the soil being loamy/clayey. A similar pattern as for the Vertisol is noticed for the Luvisol/Lixisol. In this case infiltration is most probably governed by the existence of a slowly permeable decomposing rock below appearing clayey, where gleyic properties were observed. The Plinthosol was having the highest infiltration rate because of the good drainage caused by the abundant quartz gravel and stones underlying a silty/fine sandy clay alluvium.

Although experiments carried out by Bork (1983) and Bork & Rohdenburg (1984) using the Hang double ring infiltrometer gave promising results, a number of problems were encountered. The most important problem, as also described by Christiansen (1994), occurred when attempting to fill the inner ring with water as required, due to the relatively slow water supply. During several experiments, especially on the Luvisol/Lixisol, water started flowing towards the surface along the sides of the outer ring causing false infiltration measurements. Finally, some effect from creation of macropores while inserting the infiltrometer into the soil was experienced.

Readings do, on the other hand, look realistic as compared with other experiments (Bork 1984; Gresillon 1991; Valentin 1991) and do not seem to overestimate infiltration as suggested by Christiansen (1994). Results were especially in line with findings in Burkina Faso (Gresillon 1991) where infiltration on soils with limited vegetation appeared to have often low infiltration rates (infiltration rates around 0.2 mm/minute). It is, however, recommended to increase the inflow rate of water to ensure proper upfilling of rings with water.

Measurements should only be considered indicative of prevailing hydrologic conditions since selection of test sites was fairly subjective and therefore may not reflect possible variations in infiltration within the study area.

Infiltration in relation to Precipitation

Figure 5 showing rainfall intensities of two typical rainfall events compared with the infiltration rate of the Plinthosol having the highest infiltration rate, indicates the significance of precipitation in relation to infiltration. Precipitation clearly often far exceeds the infiltration rate. Precipitation surplus, calculated as the cumulated precipitation surplus throughout the rainfall event (calculated for all rainfall events during the period 27 June to 9 August), was about 4.5 to 29 mm. The lowest values were found for the Plinthosol with the highest infiltration rate.

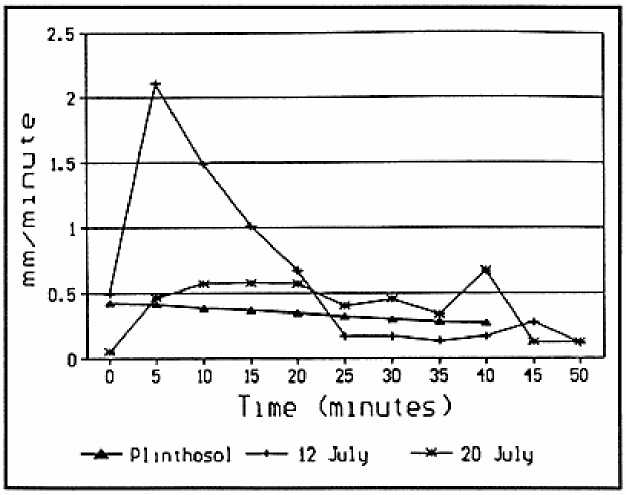

Figure 5: Rainfall intensities of two typical rainfall events (the 12th and the 20th of July) compared to the Plinthosol having the highest infiltration rate.

Studies carried out by Lamachere (1991) in Burkina Faso did, however, show that, to a larger extent, infiltration is determined by rainfall intensity and thereby raindrop impact than the total amount of rainfall. The total rainfall and precipitation surplus is, on the other hand, very important when it comes to runoff generation.

Surface Roughness and Depression Storage

A pronounced variation in Random Roughness Coefficient (RRC) was observed (table 2) ranging from 0.472 to 3.731. The random roughness values were not related to soil type whereas soil management/crops grown on the plots seemed to have an impact. The lowest roughness values were found on bullock-ploughed groundnut fields (locations 2A and 3A) characterized by a somewhat smoothened surface (figure 6). A low random roughness coefficient was also observed for the plot with rice (location 1) although management was done using a hoe. This was because of the way rice is planted in rows providing smooth surface characteristics being typical of row crops (Burwell & Lar-

Table 2: Indices of soil surface roughness and maximum depression storage.

Location	*Test site no*	*RRC*	*MRI*	*MAX DS (mm)*
Gani	*1*	*0.699*	*1.945*	*1.82*
	1A	*3.731*	*1.526*	*2.12*
Zanlerigu	*2*	*1.160*	*1.586*	*3.19*
	2A	*0.472*	*0.659*	*1.48*
Damolgzo	*3*	*2.938*	*3.101*	*6.21*
	3A	*0.963*	*1.127*	*2.44*
Yakoti	*4*	*3.491*	*0.510*	*1.44*
	4A	*1.437*	*1.782*	*3.33*

RRC = Random Roughness Coefficient
MRI = Multiple Regression Index
MAX DS = MAXimum Depression Storage

son 1969). Crops such as millet, maize and sorghum were typically planted more or less randomly in the field generally giving higher random roughness when tillage is carried out. It should be noted that due to the recording intervals of the micro-topographical measurements, random roughness resulting from aggregates in particular could not easily be depicted visually. The three surfaces appearing most rough visually (location 2, 3 and 4A) have all been weeded or tilled recently.

Differences in RRC also reflect the fact that groundnuts are generally grown on marginal land with low organic matter content. This does not enhance the build up of aggregates that could have made the surface appear rougher.

The highest value with respect to the Multiple Regression Index (MRI) is found for the recently reshaped test site no.3 where a hoe has been used. Low MRI-values are found on bullock ploughed fields (locations 2A and 3A) and on a hoe-managed site dominated by stones (test site no.4). Since the Multiple Regression Index reflects slope effects and tillage tool marks, this study carried out on virtually flat land suggests that soil management using a hoe increases soil surface roughness.

For the MAX DS (table 2) the highest value is found for the recently reshaped field where a hoe has been used. Depression values are generally low compared with values found through experiments in Burkina Faso where huge mounts are normally created after the use of a hoe.

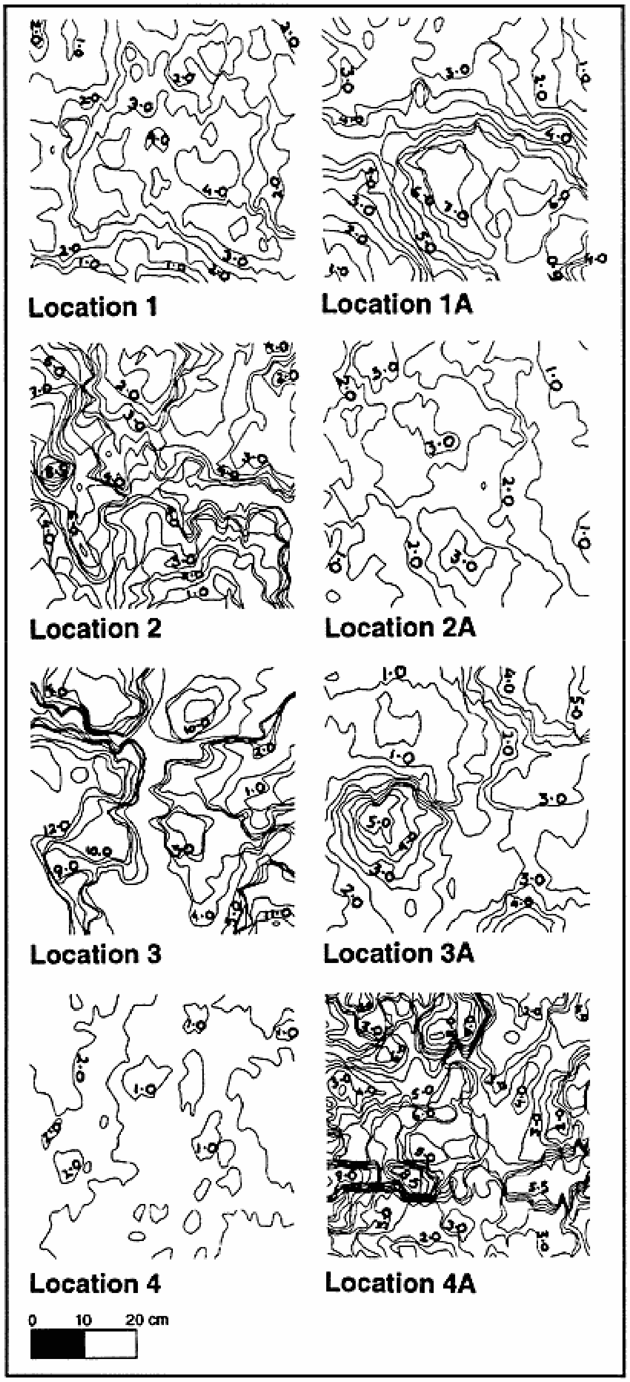

Figure 6: Micro-topographical maps for the eight test sites. Equidistance 0.5 cm.

Maximum values in Burkina Faso are between 10-20 mm immediately after tillage declining to a minimum of 4 mm

after 200 mm of cumulative rainfall (Lamachere 1991). No relationship is observed between roughness and depression storage, which is in line with findings by Edwards (1991).

If maximum depression storage values are compared with cumulated precipitation surplus during typical high intensity rainfall events, it is clear that depression storage created through existing tillage methods has a limited effect when it comes to reducing runoff. Similar observations have been made by Helming et al. (1993) based on laboratory experiments. Depression storage may, on the other hand, have some impact during less intensive rainfall events.

If soil management using the hoe is combined with conservation measures such as grass strips, good results may be achieved. Reshaping of fields has an advantage in that possible crusts may be broken thereby increasing infiltration. In general the significance of crusting should be taken into consideration not least during high intensity rainfalls. Further studies are, however, needed to elaborate upon the effect of crusting within this ecosystem.

Conclusion

The present study shows that infiltration rates measured on four different soil types in the savanna ecosystem are relatively low and in line with findings on soils in the Sahelian zone. The difference in the infiltration rate observed is determined by the soil profile characteristics.

Due to the unstable nature of the soils, measurements using the Hang double ring infiltrometer did at times prove difficult as a result of water forcing its way out along the sides of the cylinders. Problems were also encountered related to filling both rings with water fast enough. The Hang double ring infiltrometer is, however, considered to be useful in the region where access to water is limited.

When comparing typical rainfall events with the infiltration rates, it appeared that the total rainfall often far exceeds the infiltration rate. Surface roughness and depression storage were governed by soil management/crops grown and could not be related to the soil type. Random roughness was highest on hoe-tilled fields planted with millet, maize and sorghum whereas the lowest values were observed on bullock-ploughed groundnut fields and on one rice field managed by a hoe. The MRI index also showed that surface roughness is increased when using a hoe. Finally depression storage can be assumed to have limited effect when it comes to runoff reduction during typical high intensity rainfall events especially if tillage is not combined with conservation measures such as, e.g. grass strips.

It can finally be concluded that, combined with the micro-topographical characteristics observed in the savanna ecosystem, the relatively low infiltration rates create excessive runoff being one of the prime causes of erosion. The effect of crusting should, however, be investigated.

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after 200 mm of cumulative rainfall (Lamachere 1991). No relationship is observed between roughness and depression storage, which is in line with findings by Edwards (1991).

If maximum depression storage values are compared with cumulated precipitation surplus during typical high intensity rainfall events, it is clear that depression storage created through existing tillage methods has a limited effect when it comes to reducing runoff. Similar observations have been made by Helming et al. (1993) based on laboratory experiments. Depression storage may, on the other hand, have some impact during less intensive rainfall events.

If soil management using the hoe is combined with conservation measures such as grass strips, good results may be achieved. Reshaping of fields has an advantage in that possible crusts may be broken thereby increasing infiltration. In general the significance of crusting should be taken into consideration not least during high intensity rainfalls. Further studies are, however, needed to elaborate upon the effect of crusting within this ecosystem.

Conclusion

The present study shows that infiltration rates measured on four different soil types in the savanna ecosystem are relatively low and in line with findings on soils in the Sahelian zone. The difference in the infiltration rate observed is determined by the soil profile characteristics.

Due to the unstable nature of the soils, measurements using the Hang double ring infiltrometer did at times prove difficult as a result of water forcing its way out along the sides of the cylinders. Problems were also encountered related to filling both rings with water fast enough. The Hang double ring infiltrometer is, however, considered to be useful in the region where access to water is limited.

When comparing typical rainfall events with the infiltration rates, it appeared that the total rainfall often far exceeds the infiltration rate. Surface roughness and depression storage were governed by soil management/crops grown and could not be related to the soil type. Random roughness was highest on hoe-tilled fields planted with millet, maize and sorghum whereas the lowest values were observed on bullock-ploughed groundnut fields and on one rice field managed by a hoe. The MRI index also showed that surface roughness is increased when using a hoe. Finally depression storage can be assumed to have limited effect when it comes to runoff reduction during typical high intensity rainfall events especially if tillage is not combined with conservation measures such as, e.g. grass strips.

It can finally be concluded that, combined with the micro-topographical characteristics observed in the savanna ecosystem, the relatively low infiltration rates create excessive runoff being one of the prime causes of erosion. The effect of crusting should, however, be investigated.

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