Changes in Surface Runoff Due to Crust Formation and Land Conservation Techniques: The Case of On-Farm Study in Niger, West Africa

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Abstract
For studying surface runoff dynamics and testing effects of land conservation techniques, an on-farm observation was conducted at a moderately sloped (2.8%) pearl millet field in the southwestern part of Niger, West Africa, during the rainy season in 1998 and 1999. Runoff volumes and eroded soil were measured at 4 experimental runoff plots, 20m × 2m in dimension, with different treatments; millet cultivation with manure and crop residue application before the onset of the season (**MM**), millet cultivation with no fertility management (**M**), bare surface **(B**) and bare surface with stone lines at 10m interval (**BS**.) All plots received weeding tillage twice with traditional hand hoes during the season. A Tension Disk Infiltrometer was used to measure changes in infiltration rates in these plots and in the surrounding field.
Throughout the growing season, the total runoff from the **M** and the **B** amounted to 13-15% and 21-23% of the total rainfall, respectively. These two plots showed same runoff characteristics until leaf area index of the millet became significant to intercept the rain. Runoff from the **MM** was remarkably less than that of the **M** and the **B** until the first weeding tillage. This low runoff ratio was brought about by termites, which were attracted to organic matter on the soil surface and promoted good macro-pore developments. Weeding tillage had a very positive effect on infiltration because of destruction of the soil crusts on the surface. However, the crusts quickly re-established after some rainstorms. The **BS** had about 36% less runoff than the **B**. Soil erosion mostly occurred in the beginning of the season in all plots. It was not at severe degree however, since runoff distance was limited to 20m. These results suggest that soil and water conservation in the beginning of the season would be more effective.

Keywords：Sahel, Surface runoff, Crust, Termites, Pearl millet, Conservation

1. Introduction

Pearl millet (*Pennisetum glaucum (L.) R.Br.*), the staple crop of the Sahel, is originally adapted to sandy, permeable soil condition. In the southwestern part of Niger, it was mainly cultivated in the fields around the villages, situated in the middle to bottom parts of the moderately sloping wide valleys with deep sand accumulation. However drastic population growth (more than 3% year^{-1}) in the last 35 years induced an expansion of cultivated area to upstream (Fig. 1.) Being far from the villages, fertility management in such area was poor apart from fallow, and fallow itself also shortened because of high population pressure. Together with over-exploitation of natural resources in the upper valley, surface runoff increased and soil became less permeable with erosion. With the declining rainfall trend, productivity in such area has become very unstable.

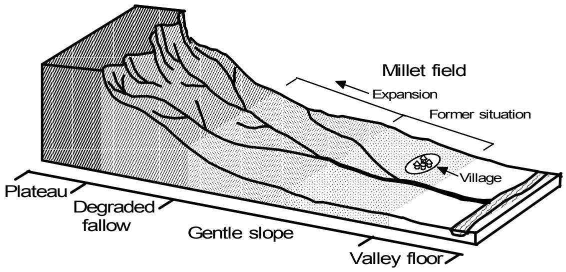

Fig.1. Topographic units in the southwestern part of Niger and situation of millet fields.

To combat desertification of the valley, raising productivity of an unit farmland, including rehabilitation of degraded land, seems to be the only sustainable solution. On-going projects in the Sahel region are employing soil and water conservation techniques to achieve this goal. The objective of this study was to quantify surface runoff characteristics in the millet field and to test effects of land conservation techniques in reducing surface runoffs. Earlier studies in the Sahel region using rainfall simulators (e.g. Hoogmoed and Stroosnijder,1984; Casenave and Valentin, 1989) have revealed that surface runoff generation is largely influenced by soil surface condition, especially by crust formation. Seasonal change of runoff rate in millet fields due to crust disturbance and reformation has been reported by Rockström and Valentine (1997). However, working mechanisms of land conservation techniques in reducing runoffs have not been well analyzed until today. This paper therefore puts emphasis on revealing these points.

2. Materials and Methods

2.1 Field Site

The study was conducted in the experimental farm of Japan Green Resources Corporation in Magou village in the canton of Torodi, situated about 60km southwest of the capital Niamey, Niger, West Africa (13° 6' North, 1° 44' East). The climate is Sudano-Sahelian according to Sivakumar (1989). Rainy season generally occurs for 3 months and a half from mid June to end of September with the average rainfall of 566.8mm (1961-1990, Sivakumar et al.; 1993).

2.2 Millet Cultivation Practice

Cultivation of pearl millet in the southwestern part of Niger retains a simple and extensive style from long time ago. With more than 20mm of rainfall in the beginning of the season, farmers sow the grains by creating 5,000 to 10,000 pockets per hectare with digging hand hoes. There is no soil preparation before sowing. If subsequent rain does not fall for more than a week and seedlings happen to die, sowing is repeated

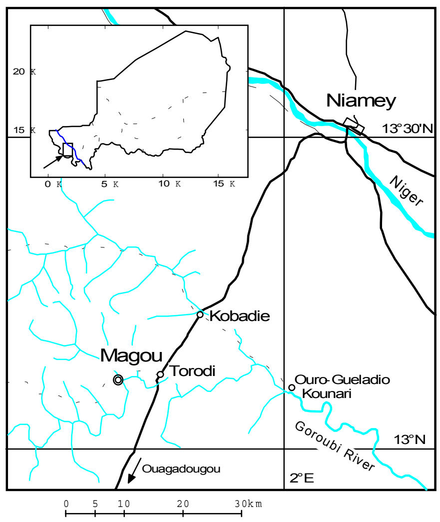

Fig. 2. Situation of the study site.

again. About 2 weeks after sowing, weeding tillage is carried out by hand hoes. A traditional hoe called *hilaire* cuts the roots of the weeds at depth of about 3cm underground when pushed, and pulverizes soil when pulled back. Thinning and transplantation are carried out at the same time. Since all labor depends on hands, it takes farmers a few weeks to complete weeding in their fields. Weeding is usually carried out once again in the season. After the harvest, farmers cut down stalks at bottom and residue is left on the ground. However a few remains until next season because some portion is taken out for women's craft works like blinds, and large portion is eaten up by cattle grazed in the fields during the off-cultivation season.

2.3 Experimental Design

The study was carried out using 4 runoff plots built on a bottom of sloped millet field (2.8%.) Soil type was acidic sandy soil, which is *Sandy Siliceous Isohyberthermic Psammentic Paleustalf* by the USDA classification. Surface soil had clay fraction less than 5% and sand dominated more than 80%. Although it had relatively high water conductivity, it was highly susceptible to crust formation on the surface with high intensity rainfalls.
Four plot (in a dimension of 20m x 2m) with different treatments were set up as shown below:

MM: Millet cultivation with manure application (mulching added in 1999),
M : Millet cultivation with no inputs,
B : Bare plot,
BS: Bare plot with Stone Lines as tied ridges.

In the **M** and the **MM**, pearl millet (ICMV89305) was cultivated at density of 10,000 pockets ha^{-1}. In the **MM**, farmland manure consisting of cattle dung and crop residue was thinly applied on the surface at a rate of 1.5t ha^{-1}. No tillage for mixing was performed. After the rainy season of 1998, crop residue was left on the surface as mulching in the **MM** only. It amounted to about 2.5t ha^{-1} and cattle was kept out. Before the onset of the season in 1999, manure was applied again at the same rate. In the **M**, neither manure nor crop residue was applied in both years. Weeding tillage was carried out twice during the season in all plots. In the **B**, slight weed growth was observed in the beginning of the season, but at negligible scale. Adopted stone line for the soil and water conservation in the **BS** is a common structure in the Sahel region. Ironstones collected from plateaus are buried half to two thirds of their height underground, close together, to form a tied ridge along a contour line. It does not stop runoff completely but breaks the speed of runoff and enhances infiltration and soil deposition.
Rainfall was measured with an automatic rain gauge (Campbell Scientific TE525M). Runoff volume was determined by measuring the level of water collected in the reservoirs, 1m x 1m in dimension. Runoff intensity was also measured in the **MM** and the **B**, using tipping bucket flow meters (Ikeda Keiki, Japan, TQX-2000, capacity 2*l*). Data was stored in a datalogger (CR10X, Campbell Scientific) at an interval of 1 minute in 1998 and of 20 seconds in 1999. Eroded soil was collected after each rainstorm and air-dried to measure the mass.
Soil moisture was measured using a neutron probe (Didcot Instrument, Type I.H.III). Access tubes in PVC, 5cm in diameter, were installed to depths of 2m. The probe was calibrated to the soil and the PVC tube condition. Measurements were carried out at every two weeks' interval with a depth increment of 15cm.
A Tension Disk Infiltrometer (Soil Moisture Measurement) with a disk diameter of 20cm was used to measure changes of soil surface hydraulic conductivity due to crust formation and treatments. Measurements were also carried out in the various points of the adjacent field.

3. Results and discussion

3.1 Rainfall trends

Rainfall during cultivation amounted to 512.4mm and 683.6mm in 1998 and 1999, respectively. In Fig. 3, daily rainfalls in 1998 and 1999 are shown. While rainfall in 1998 was close to the average and typical in distribution, in 1999 it exceeded the average by far with abundant rainfall in the later season.

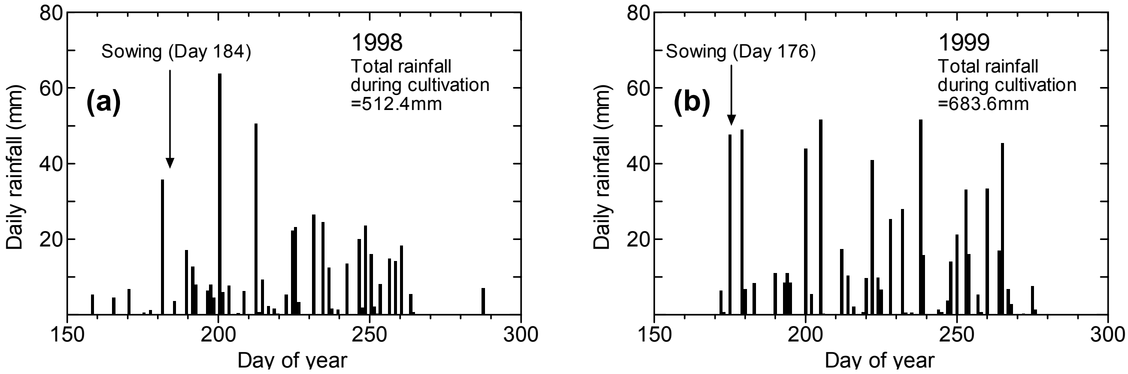

Fig. 3. Daily rainfall distribution in 1998 (a) and 1999 (b).

3.2 Cumulative Runoff Trend

In Fig. 4, cumulative runoffs are plotted against cumulative P_r . P_r here is defined as rainfall depth of the event which caused any runoff in either of 4 plots. Eliminating rainfall events with no runoff generation makes understanding of the trend easier. P_r, amounted to 379.2mm in 1998 and 537.4mm in 1999. Cumulative runoff from the **BS** in 1998 is not shown because error in measurements occurred in the beginning of the season, which disabled the calculation of cumulus. In both years, similar phenomena were observed, which were; i) a lower runoff rate (runoff / P_r) in the **MM** in the beginning, compared to the **M** or the **B**, until first weeding tillage, ii) nearly same runoff rates in the **M** and the **B**, until after the first weeding tillage, iii) a decrease of runoff rates for all plots after weeding tillage, iv) a lower runoff rate in the **BS** compared to the **B**. The reasons for these phenomena are discussed below.

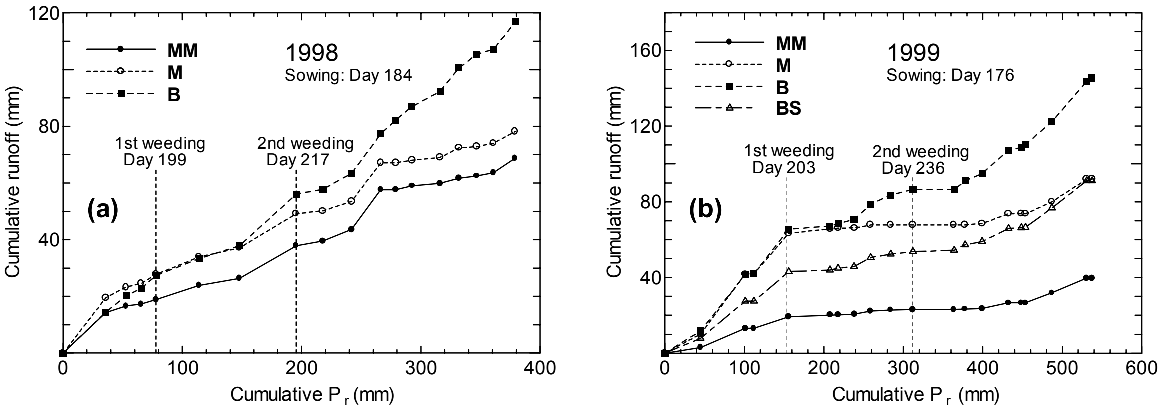

Fig. 4. Cumulative runoff against Cumulative P_r in 1998(a) and 1999(b).

3.3 Effect of manure and mulch application

The lower runoff rate in the **MM** in the beginning of the season was attributed to an activity of soil dwelling termites. When manure was applied before the onset of the season, in about a week, termite sheeting covered it all. Soil dwelling termites are known to directly ingest the organic matter they remove when foraging, and they take the matter to their nests a few meters underground where they grow fungus for their feed. As a result, soil crust, which developed on the surface, was destroyed and water infiltrated through the macro-pores they created. Mando (1997, 1998) reported in a series of his studies in Northern Burkina Faso that attraction of termites by mulching was very effective in rehabilitating the crusted soil. In 1999, this effect was more pronounced than in 1998, due to the addition of crop residue as mulches. Although crop residue was not all eaten up before the onset of the season like manure, termite sheeting again covered most of its part touching the ground. Presence of mulch may also have served in increasing the surface roughness, which slowed surface runoff and enhanced infiltration.

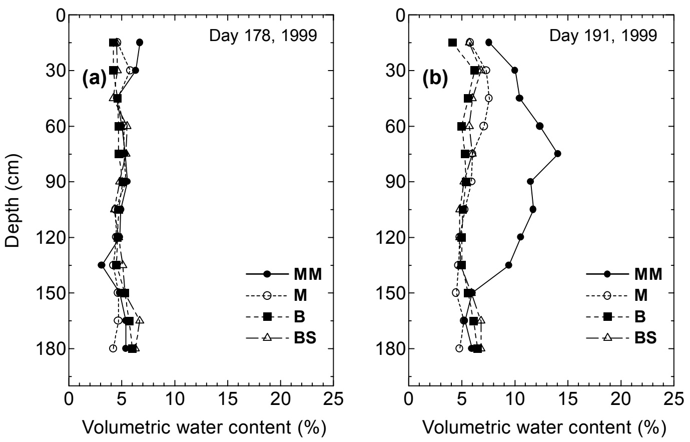

Fig. 5. Soil moisture storage in the plots of different treatments after the sowing rain (a) and before the first weeding (b).

Figure 5 shows the changes in soil water storage in the plots of different treatments in the beginning of the season in 1999. There was no significant difference in soil moisture profile between the plots after the sowing rain. However, much more infiltration into deep profile occurred in the **MM** with subsequent rains of 49.1mm and 6.9mm. A well-developed vertical macro-pore network, brought about by termites may explain this phenomenon. Soil moisture storage in the **MM** was 69.1mm more than that of the **M**, which exceeded the difference of cumulative runoff depth until that time. Since the access tubes were placed only one per each plot, spatial variability of infiltration or macro-pore network may have influenced.

The higher infiltration in the **MM** held for several rains until the first weeding tillage. Figure 6 (a) is a comparison of runoff intensities in the **MM** and the **B** before the first weeding. It was the third rain exceeding 40mm since the onset of the season. Runoffs were sensitive to monomodal distribution of rainfall in both plots. The peak runoff intensity had more than 2.5 times fold of difference. After the weeding, however, runoff rate of the

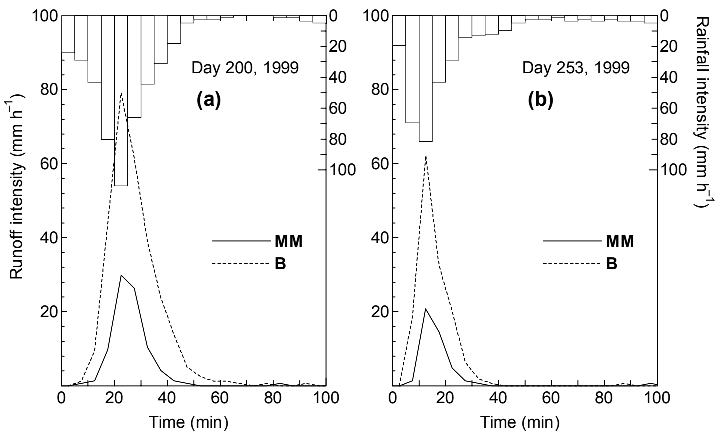

Fig. 6. Rainfall-runoff intensity relation at 5 min interval before the first weeding (a) and 77 days after sowing (b) in 1999.

MM became same as that of the **M** for the rest of season (Fig. 4). It meant that this effect had diminished with disturbance of thin surface layer though better macro-pore network created by termites may still have remained in the underlying soil of the **MM**.

3.4 Effect of millet growth

From Fig. 4, same runoff rates of the **M** and the **B** in the beginning of the season confirmed that until a certain growth stage, millet field without any input could be assumed as a bare field. The difference became significant, a few rainstorms after the first weeding tillage onward. It was 29 and 38 days after sowing, for 1998 and 1999, respectively. The Leaf Area Indices at these moments (total leaf area of a plant / unit cultivated area [m^2 m^{-2}]) were estimated to be 0.2-0.3. These were the moments, when millets were tillering fast after thinning and LAI was increasing rapid.

When LAI reached around 1.0, runoff rate of the **M** was sometimes less than 1/5 to that of the **B**. Figure 6 (b) is again a comparison runoff intensity in the **MM** and the **B**, at day 253 in 1999. As stated above, runoff from the **MM** at this moment could be assumed same as that of the **M**. LAI was around 0.9. When hydraulic conductivity was measured in between rows of plants in the **MM** and in the **B**, no significant difference was found. The reduction in runoff may be attributed to interceptions of rain by plants, or to partially high conductivity of soil under the plant. When millet flowered and LAI decreased due to fall down of the leaves, the difference became less. At the end of the season, cumulative runoff differences between the **M** and the **B** were 38.6mm and 53.4mm in 1998 and 1999, respectively.

3.5 Effect of tillage

The change in runoff rate of the **B** reflected the sole effect of weeding tillage. This contributed to breaking down of soil crust that limited infiltration. Consequently, weeding largely increased infiltration. However, crust redeveloped after a few rainfall events. 1n 1999, recovery of crust was slower than in 1998 because the weeding was delayed and larger quantity of weed residue was left in the tilled soil. Therefore runoff generation was suppressed by an increased roughness and a slowing of crust redevelopment. In Fig. 4, Cumulative runoffs in the **B** before the 1st weeding and from the 2nd rainstorm after the 2nd weeding onward had almost linear shape. This suggests that crust was fully developed during these periods. Average runoff ratios against P_r for these periods were 36.1% and 35.3% in 1998 and 1999, respectively.

3.6 Effect of the stone line

The **BS** showed lower runoff rate than the **B** and yet the trend of the change was very similar (Fig. 4.) When runoff occurred, water ponded on the upper side of the stone lines. The depth of ponding was limited to a few centimeters and it was released downstream slowly through the gap between the ironstones. Figure 7 shows the correlation of runoff depths between the **B** and the **BS** for each runoff event. A good linear relation was obtained with r^2=0.92. The regression line passed near (0,0), which confirmed that stone lines do not stop the runoff but rather breaks

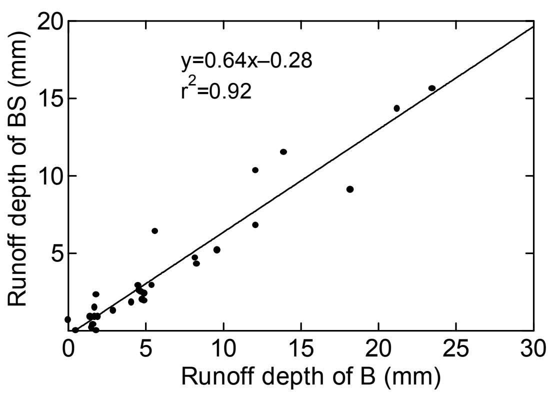

Fig. 7. Correlation of runoff depths between the B and the BS in 1998 and 1999.

the speed of the flow and enhances infiltration. Moisture storage in the profile, read with the neutron probe, was at all times greater in the **BS** than in the **B**. The access tube was situated 4.3 m away from the stone line upstream. Therefore the effect of enhanced infiltration was not limited to the vicinity of stone lines.

3.7 Soil erosion

Table 1 shows the dry mass of eroded soil from each plot during the growing season. Since soil was recovered from reservoir tanks after pumping out water with fine fraction colloidal, only the coarse fraction was counted. Soil erosion was generally more severe in the beginning of the season. It was because of the coarse fraction outcropping loose on the surface as a result of a formation of structural crust (van der Watt and Valentin, 1992) in the former season. Therefore it could easily be washed out by runoffs in the beginning of the following season when the soil surface was dry. After the weeding tillage, same phenomena probably took place again, but soil surface was wetter and more coherent, hence erosion was not that severe. In the **B**, soil erosion increased towards the end of the season again, because there was no plant shelter and surface was probably drier than in the **MM** or the **M**. In 1998, the difference between the **M** and the **MM** was not significant. In 1999, addition of mulch reduced runoff in the **MM** in the beginning and it kept the erosion also at a low degree. The effect of stone line was considerable, when the **BS** was compared to the **B**. Total amount of erosion in the plots were not at severe degree because runoff path was limited to 20m and only sheet flow occurred. Erosion increases drastically when rill flows occur and which seems the common erosion cause in the Sahel region. Therefore conservation works like stone lines to break the speed of flow should be very effective in preventing soil erosion.

Table 1. Dry mass of water- eroded soil during the growing seasons

		Mass of eroded soil (coarse fraction) t ha^{-1}			
		MM	**M**	**B**	**BS**
1998	Before 1st weeding	1.14	1.01	2.44	0.98
	Before 2nd weeding	0.23	0.15	0.80	0.15
	After 2nd weeding	0.40	0.15	0.99	0.20
	Total	1.77	1.31	4.23	1.33
1999	Before 1st weeding	0.88	1.78	0.69	0.42
	Before 2nd weeding	0.29	0.22	0.37	0.22
	After 2nd weeding	0.19	0.18	1.79	0.21
	Total	1.36	2.18	2.85	0.85

Table 2. Seasonal runoff rates of plots with different treatments.

Year	Total Rainfall during cultivation (mm)	Runoff rate (%)			
		MM	**M**	**B**	**Bs**
1998	512.4	13.4*	15.3	22.8	-
1999	683.6	5.8**	13.5	21.3	13.3

*Manure only: **Manure and mulch

3.8 Seasonal runoff rate

Table 2 summarizes the seasonal runoff rates (total runoff /total rainfall) from each plot in 2 growing seasons. Runoff rates were similar for the **M** and the **B** in both seasons in spite of considerably different rainfall pattern. Runoff rate of the **MM** in 1999 was greatly reduced by addition of mulch. If stone lines were combined to millet cultivation, farther reduction of runoff could be expected.

3.9 Spatial variability of surface permeability

The adjacent millet field was cultivated in the same manner as in the **MM** during the two growing seasons. However, the soil water regime differed from place to place. Figure 8 shows the soil water storage under two different representative surface conditions. They are namely *Hondou* and *Gangani* in the local language. Hondou means sandy soft surface and Gangani means clayey, hard, and eroded surface. The experimental runoff plots were situated at the bottom of the slope and it happened to belong to Hondou. Gangani was found in the middle to upstream of the slope. There was only a slight difference in soil textures and yet saturated hydraulic conductivity was considerably different. Figure 9 shows final infiltration rates from the Tension Disk Infiltrometer with at pressure head of –3cm H_2O around the access tubes of Fig. 8. For each location, 3 measurements were carried out on the crust, followed by another 3 measurements after removal of the crust. The crust was at full development at the time of measurement. As shown in Fig.9, final infiltration flux in Hondou was 2 times and 1.4 times greater than in Gangani for the underlying soil and the crust, respectively. Final infiltration rate of the crusted surface was 28-40% lower than that of the underlying soil. When these values are considered, runoff rates in Gangani should be greater than presented in Table 2. Detailed analysis of collected data and modeling must bring quantifying this issue.

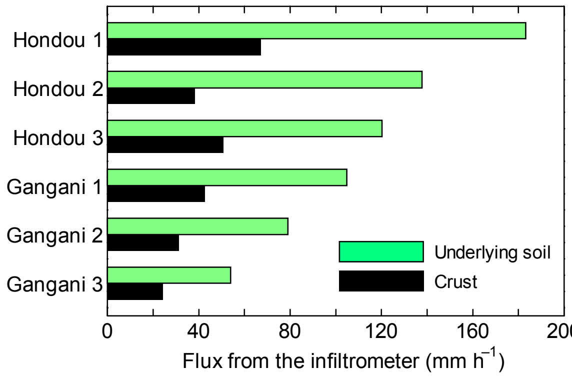

Fig. 9. Comparison of final infiltration rate from the Tension Disk Infiltrometer in Hondou and Gangani surfaces

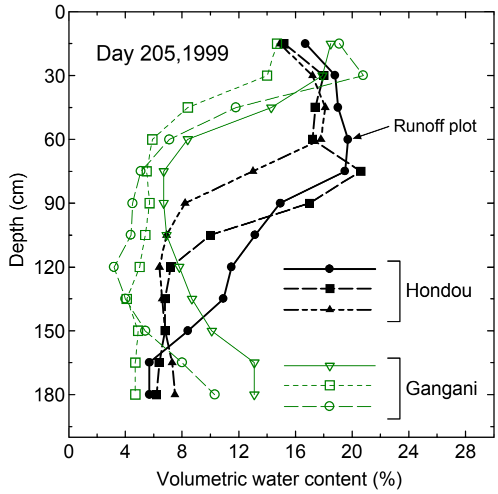

Fig. 8. Soil water storage difference in Hondou and Gangani.

4. Conclusion

On-farm study of surface runoff in pearl millet field made the followings clear:

i) Application of manure in combination with mulch greatly reduces runoff at the onset of the season, due to attraction of termites that break the crust on the soil surface and create good macro-pore network in the soil to facilitate infiltration,

ii) At 30-40days after sowing, growth of millet becomes significant to reduce runoff in combination with weeding,

iii) Stone line is effective in breaking the speed of flow and this results in better infiltration.

Since rainfalls at the onset of season are vital for the establishment of millet and they often happen to be unstable, reduction of runoff in the beginning of the season seems very important. Combination of techniques above would be very effective.

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