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Water, nutrients and slope position in on-farm pearl millet cultivation in the Sahel

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Abstract

In the Sahel, short periods of intra-seasonal drought, caused by unfavourable rainfall distribution, often have stronger effect on crop growth than fluctuations in annual rainfall. The interactive effects of nutrient deficiency and water shortage (during panicle initiation, flowering and grain filling) on yield and yield components of pearl millet (*Pennisetum glaucum* (L.) R. Br.), were studied on-farm along a cultivated slope, during three years with close to average annual rainfall. Grain yield was correlated to plant nutrient availability but not to annual rainfall, which was explained by the capacity of the crop to compensate for damage caused by water shortage during early growth phases. The performance of each yield component was positively correlated to cumulative rainfall during the growth phase when it was formed. Leaf area index (LAI) was very low, and leaf development followed rainfall distribution. Water and nutrients interacted during each growth phase for all fertility levels. Fertilised millet suffered less during water shortage at panicle initiation and at grain filling compared to non-fertilised millet. However, compared to favourable soil water conditions yield components were systematically lower for all treatments, indicating the synergistic effect of water and nutrients. The results suggest that water availability plays an exclusive role during flowering. Grain number dropped significantly due to water shortage and was similar for all treatments. Despite extremely high spatial variability in yields (varying with a factor 46 within the field), a significant slope effect was observed, of progressively increasing yields when moving downslope. Spatial redistribution of surface runoff resulting in higher soil water availability on lower slope positions, contributed to the yield gradient, which was reinforced for fertilised millet. For each drought period, yield components suffered systematically more upslope than downslope. This slope effect was smoothed out for manured millet, which indicates that manure increased soil infiltrability on crusted zones upslope. The slope interaction observed here – indicating that downslope (i) the risk for crop failure during droughts is lower and (ii) the response to fertilisers is greater – suggests that farmers can benefit relatively more from fertilisers applied in lower parts of the watershed. Taking advantage of spatial soil and water variability is an interesting system of low technology precision farming, which combined with water harvesting systems to master droughts, can constitute options for increased crop yields in the Sahel.

Introduction

Low-input rainfed agriculture is, and will be in the foreseeable future, the dominant source of food in the semi-arid and dry sub-humid tropics (Parr et al., 1991). In the semi-arid Sahel region, with an annual rainfall of 150–600 mm and a cumulative potential evapotranspiration (PET) of 1800–2500 mm (Breman and Kessler, 1995), there is a tendency of declining yields of staple crops like pearl millet (*Pennisetum glaucum* (L.) R. Br.) and sorghum (*Sorghum bicolor* (L.) Moench) (Matlon, 1990). Causes underlying declining yields include interactions between chemical and physical land degradation, agricultural drought, and population driven transitions in agrarian systems (Falkenmark and Rockström, 1993; Rockström and Ada, 1993). So, even though water is a principal constraint in dry-

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land agriculture (Lal, 1991), the on-farm reality for the Sahelian farmer includes factors such as soil nutrients, soil surface conditions, and relief, which also influence crop production. Water is a constraint primarily due not to low annual rainfall, but rather to high intra-annual variability, both temporal and spatial, which results in coefficients of variation (CV = standard deviation / mean × 100) exceeding 20% (Nicholson, 1981; Sivakumar et al., 1993). This, in combination with high evaporation losses (up to 50% of annual rainfall) and a dominance of sandy soils with low water holding capacity, makes periods of soil water shortage during the growing season common (Rockström, 1995).

Drought affects those plant parts which are undergoing rapid development. The actual damage on a crop will therefore depend on the timing of the occurrence of a water stress with respect to development stage. Pearl millet is a drought tolerant crop, well adapted to growth in sandy soils under low soil water regimes (Kassam and Kowal, 1975). Yet, it remains a cereal with characteristics common to all grain crops; the initiation and development of reproductive organs is restricted to well-defined growth phases (GP), and drought during these periods results in irreparable losses (Fussell et al., 1980; Maiti and Bidinger, 1981). The vegetative phase (GP1) covers emergence to panicle initiation. Growth conditions are initially reflected in the number of established millet stands (hills) per unit area, and thereafter in the number of tiller stems (Begg, 1965). Thus, the yield components hills 100 m^{-2} and panicle number, are a testimony of the growth conditions during GP1. The panicle development phase (GP2) covers panicle initiation to flowering. Growth conditions are reflected in the yield component grain number. The grain filling phase (GP3) begins with the pollination of the main shoot and ends with the maturity of the tillers. Growth conditions will govern the weight of individual grains, i.e. the yield component single grain mass. As growth phases are highly independent of each other, periods of stress can be traced in the poor development of a yield component (Lambert, 1983; Ong and Monteith, 1984). The effects of water stress on pearl millet which have been studied under controlled forms (e.g. irrigation trials on station) show reductions in yield, but also in the capacity of millet to adjust to periods of water shortage (Gregory and Squire, 1979; Ibrahim et al., 1985; Mahalakshmi et al., 1988; Squire et al., 1984). Yet, very little is known about the behaviour of pearl millet in farmers' fields with frequent dry spells.

Farmers in the Sahel cultivate pearl millet on chemically poor, crust prone, sandy soils, generally without adding external nutrient inputs. In Niger, millet yields are low, varying from 150 kg ha^{-1} to 550 kg ha^{-1} during a drought and a normal year, respectively (McIntire and Fussell, 1989). Fertiliser experiments have been performed on-farm in the Sahel, showing the beneficial effect of phosphorus (P) on crop yield (Bationo et al., 1992), and that the crop can fail to respond to nitrogen (N) during severe drought years (Christianson et al., 1990). Payne et al. (1995) reported an increase of transpiration efficiency of millet shoots subject to water stress, while P use efficiency decreased with stress. Very few on-farm studies exist on P and N efficiency in crop growth under sub-optimal rainfall conditions. In the Sahel, millet cultivation and semi-nomadic pastoralism co-exist, giving farmers relatively easy access to manure compared to mineral fertilisers. Even though only small quantities of nutrient poor manure are applied (de Rouw et al., 1997; Quilfen and Milleville, 1983), these forms of traditional fertilisation deserve more attention (Landais and Lhoste, 1993).

In the sub-humid, Sudanian savannah in West Africa, farmers exploit a soil water and fertility gradient by growing cereal crops in patterns adapted to toposequence and soil characteristics (van Staveren and Stoop, 1985). In the semi-arid Sahel, millet is often cultivated along gentle slopes in fields adjacent to degraded, permanent fallow and plateau zones upslope, which produce large volumes of surface overland flow. Different soil water and nutrient availability along these slopes can influence crop development. Cropping patterns are, however, more uniform in the Sahel compared to the sub-humid savannah zone, which raises the question whether soil water and fertility gradients actually exist and, if so, to what extent they can be better exploited? There are no studies, conducted on-farm, which examine the interactive effects of water and plant nutrient availability on crop growth along a cultivated slope where the plant available soil water is determined not only by rainfall distribution, but also by the redistribution of surface overland flow. This paper presents results from three years (1994–1996) with close to average cumulative rainfall, but with contrasting rainfall distribution, causing intermittent droughts during different phases of millet growth. The objectives are to analyse, on different slope positions in a farmer's field, (i) the effect of water availability on yield and yield components, and (ii) the interactive effects on crop development of soil water shortage and the application of small quantities of fertiliser and manure.

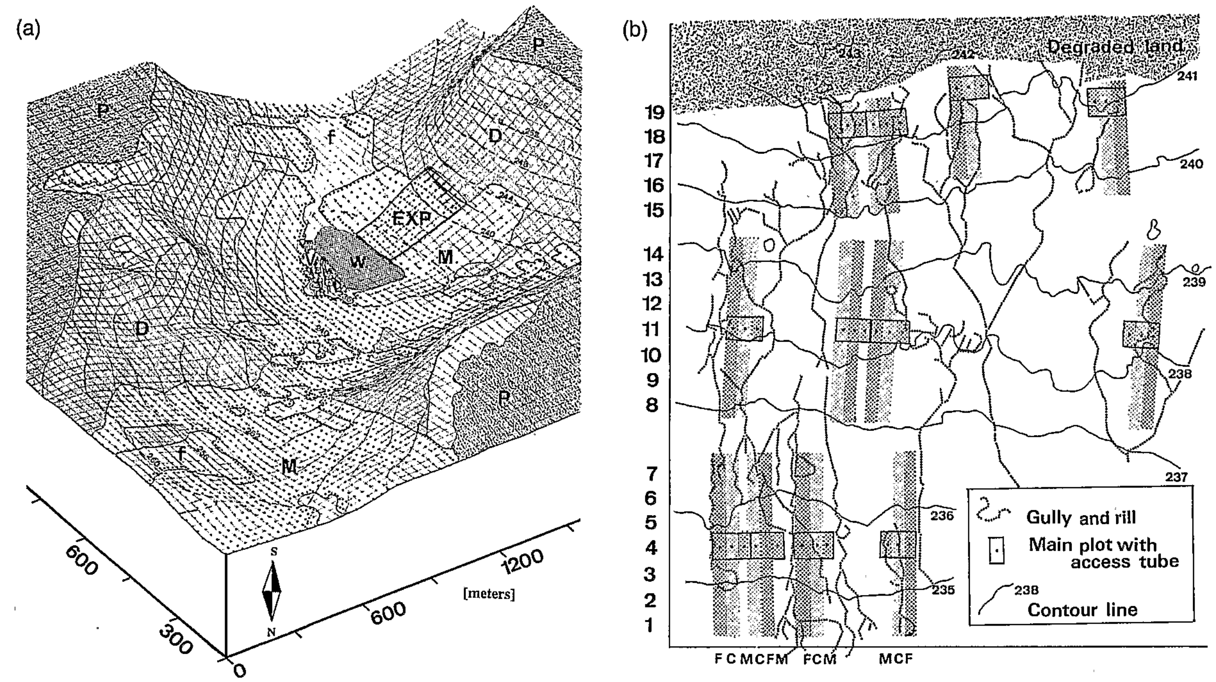

Figure 1. (A) The Samadey watershed with a description of the catena. Letters indicate plateau (P), degraded area (D), millet field (M), experimental field (EXP), village (V), fallow (f), temporary wetland (W). (B) Experimental design. Access tubes are marked with dots in the middle of main subplots. Numbers of subplots are indicated on the y-axis, and the allocation of treatments on the x-axis (F=fertiliser, M=manure, C=control).

Materials and methods

Experimental site

The experiment was conducted in a farmer's field located in the Samadey watershed, situated 70 km east of Niamey, Niger (02°41′50″ E, 13°35′5″N). The 315 × 270 m millet field occupied a gentle and homogenous slope (2–3%), and formed a part of a typical toposequence of the Sahelian landscape (zone EXP in Figure 1A). Upslope we find non-cultivated gravely plateaux (zone P in Figure 1A) and below the relatively steep escarpments start the valley systems. Closest to the plateaux the soils are shallow, crusted and usually not cultivated (dominated by the shrub *Guiera senegalensis* J. F. Geml.) (zone D in Figure 1A). Further downslope the eolian sand deposits are sufficiently thick to allow cultivation of millet. Millet cultivation continues downslope until the sandy soil gradually becomes more clayey, marking the transition zone where the farmer starts cultivating sorghum (zone W in Figure 1A) (Estèves and Lenoir, 1994; Rockström and Valentin, 1997). The experimental field has been continuously cultivated with pearl millet for at least 25 years. The field is subject to a high degree of soil crusting, resulting in production of surface runoff (R_{off}) amounting to an average of 12% of annual rainfall at the upslope position and 7% at the downslope position (mean for 1994–1995) (Rockström and Valentin, 1997). The field also receives large volumes of Run-on water (R_{on}) (amounting to >100% of rainfall depth for intensive storms, calculated on a plot basis), originating from the degraded zones in the upper parts of the watershed (zone D and P in Figure 1A). The soil texture is uniformly sandy, ranging from 91.2% sand, 5.7% silt and 3.1% clay in the surface layer (A horizon) upslope, to 90.4% sand, 5.8% silt and 3.8% clay downslope. The content of organic matter in the A horizon is very low, but is slightly higher downslope (0.27%) than upslope (0.23%). The soil is poor in plant extractable minerals, however, the amount increases moving downslope (mean values for upslope positions: ECEC = 17.9 meq 100 gr^{-1} soil, Bas Saturation (BS) = 62%, for downslope positions: ECEC = 24.6 meq 100 gr^{-1} soil, BS = 80%). The entire slope has been classified as an Ustic

Isohyperthermic Typic Haplustult (U.S.D.A. Soil Taxonomy) (Rockström and Valentin, 1997).

Agronomic details

The manual cultivation practices for millet have been described in the region by McIntire and Fussell (1989), and in the study area by Seybou (1993). Millet cultivation in the experimental field followed local practices. Sowing was performed after the first rain (over 15 mm) in small pockets (10–15 cm deep), dug with a hand hoe, a “daba”. Thinning was done to 3 plants hill^{-1}, 20–25 days after sowing (DAS). Weeding was carried out twice, 20–28 DAS and 69–78 DAS with a “hilliare”, a long hand hoe which cuts the soil 2–5 cm under the surface. The millet crop in the experiment was sown at a density of 10,000 hills ha $^{-1}$. The non-photosensitive cultivar CIVT (Composite Inter-Varietal de Tarna) was used, which is similar to the traditional varieties in the region. Sowing and harvest were carried out on 16 June and 28 September 1994, on 20 June and 25 September 1995, and on 3 June and 23 September 1996, respectively.

Experimental design

Millet performance along the slope was studied by creating elongated plots from the top to the bottom of the slope (Figure 1B). Each single plot was split into 19 subplots. The uppermost subplot (No. 19) was situated at the natural limit of the millet field to the degraded fallow zone, and the lowermost subplot (No. 1) was located at the downslope limit of the field. Subplots were adjacent to each other, except for an interruption of 30–35 meters between plots No. 7 and 8, and between plots No. 14 and 15, resulting in three clusters of plots along the slope: upslope, midslope and downslope. Due to irregularities in the field, caused by the natural extension, trees, gullies, termite hills, foot paths and severely eroded areas, each cluster was adjusted sideways in order to assure a location of all plots within areas normally cultivated by the farmer (only rills pass through the plots). The area around the plots was also cultivated.

Main subplots were designated at three slope positions for intensive observations: subplots No. 18 (upslope), No. 11 (midslope) and No. 4 (downslope), with a size of 16 × 6 meters. The remaining 16 subplots each had a size of 15 × 6 meters. The experiment was a randomised block design with one factor, fertilising, and three treatments, control, manure, and fertiliser (NP_{fert}), with 4 replicates. Control plots represented the farmers practice with zero input of fertilisation. The manured plots received 5 t ha^{-1} of dry cow dung, corresponding to the maximum quantity observed on millet fields in the region (de Rouw et al., 1997). This manure was gathered from fields and enclosures and applied in March each year before the onset of the rainy season. The dung was poor in nutrients, the input of 5 t ha^{-1} corresponded to 6.2 kg ha^{-1} and 11.6 kg ha^{-1} of total P for 1994 and 1995 respectively, 0.4 kg ha^{-1} of ammonium (NH_4) and 0.03 kg ha^{-1} of nitrate (NO_3^-) for 1994, and 6.5 kg ha^{-1} of total N for 1995 (the richer dung in 1995 was due to a larger proportion originating from enclosures). Carbon content, measured only in 1994, amounted to 1360 kg ha^{-1}. NP_{fert} plots received 13.2 kg P ha^{-1}(single superphosphate), which was incorporated manually into the soil in May before the onset of the rainy season, and 30 kg of N ha^{-1}, applied as Urea (45%) in two applications (41 and 62 DAS 1994, 33 and 49 DAS 1995, and 31 and 51 DAS 1996). Due to practical constraints manure could only be applied on the main subplots.

Measurements

Green leaf area (LAI, m^2 m^{-2}) was measured from destructive sampling using a conveyor belt assisted image analysis system (Delta-T DIAS system with conveyor belt unit, Delta-T Devices Ltd). LAI was measured 6 times during the growing season, every 14 days, starting at approximately 25 DAS. In each main subplot two millet hills were grouped in one sample, giving a total of 36 samples (4 for each treatment per slope position). At least 20 samples were measured through the conveyor belt unit for each LAI measurement. All leaf samples were oven dried at 80 °C for 24–36 hours and then weighed. Remaining LAI values were calculated through linear regression from leaf dry weights. In main subplots grain yield (kg ha^{-1}) and above ground biomass (kg ha^{-1}) were determined, as well as the yield components: number of hills, panicle number, grain number, and single grain mass. In the subplots only grain yield, grain number and single grain mass were measured. The harvested area was 14 × 5 m in the main subplots and 15 × 5 m in the subplots.

Rainfall was measured with a recording rain gauge located at midslope position. The annual rainfall amounted to 595.5 mm in 1994, 517 mm in 1995, and 487.5 in 1996, which is slightly above and below the long term average of 560 mm (calculated for the period

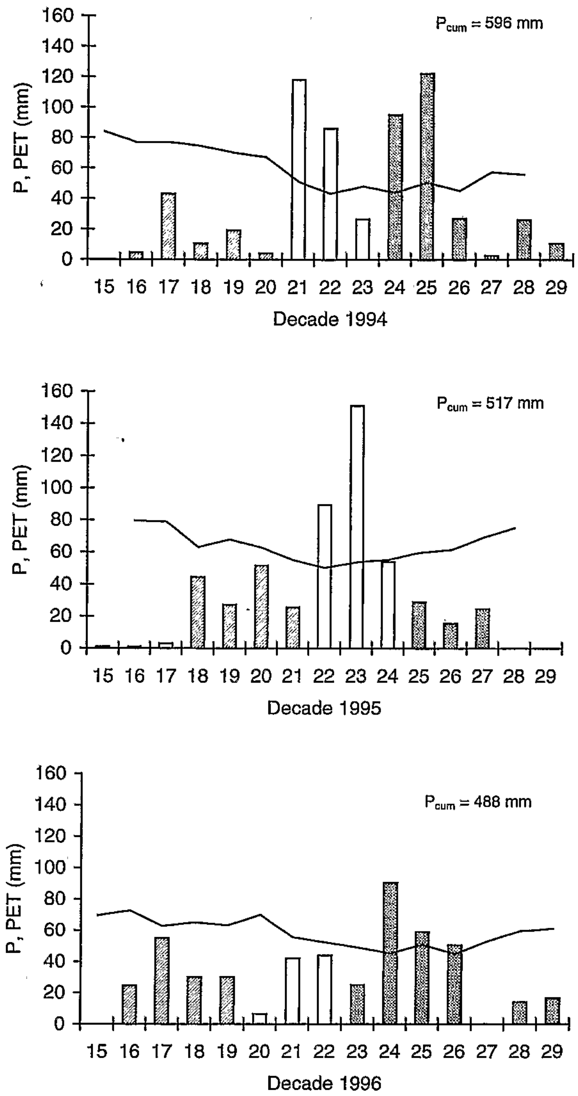

Figure 2. Rainfall distribution (per decade) and potential evapotranspiration (Penman) (per decade) in Samadey 1994–1996.

1960–1989) for the Samadey watershed (Le Barbé and Lebel, 1997). Field water holding capacity (FC) was measured over a depth of 0–60 cm at 36 observations points (2 per subplot) along 2 plots (block 1 and 3) from upslope to downslope, after 7 rainfall events in 1995 using Time Domain Reflectrometry technique (a Trase TDR, Soil Moisture Equipment Corp.).

Retention and conductivity characteristics were measured in the laboratory from undisturbed 300 cm^3 samples using the multi-step outflow method (van Dam et al., 1994) and a 15 bar ceramic plate extractor (for pF = 4.2 and pF = 3). Root observations were carried out 88 DAS in 1994, and 44, 66 and 94 DAS in 1995, through extraction of soil cores (20 cm long and 5.7 cm in diameter) down to a depth of 140–260 cm (depending on the estimated maximum root depth at sampling). At each slope position two grouped samples from 5–10 soil cores were taken, at a distance of 50 cm from each millet hill. Root length densities (cm cm^{-3}) were calculated after washing and sieving of soil samples (first with 0.5 mm then 0.125 mm sieves), using Tennant's method (2 cm grid) (Tennant, 1975).

Soil water was monitored from one access tube in each main subplot, down to a depth of 300–340 cm, using two neutron probes calibrated on site (a SOLO 25S, Nardeux Company, and an IH II Probe, Didcot Instrument Company). Measurements were carried out immediately after each rainfall event and then 2 and 4 days after the event. During the 1994 season there were no access tubes in the manured plots (giving a total of 24 tubes 1994, and 36 tubes 1995 and 1996). Data from access tubes were used to compare soil water contents between the three slope positions, which means that all soil water data presented here are mean values from 8 (1994) to 12 (1995–1996) access tubes.

Results

Soil water shortage

Field water holding capacity from TDR measurements averaged 0.125 m^3 m^{-3} for the whole field (FC$_{\text{max}}$ = 0.18 m^3 m^{-3}, standard deviation (SD) = 0.017 m^3 m^{-3}). Retention curves show that at wilting point (PWP) (pF = 4.2) soil water content increases with depth from 0.022–0.038 m^3 m^{-3} in the upper soil layers (0–80 cm), corresponding to a soil water storage of 28 mm, and amounts to a mean of 0.031 m^3 m^{-3} in deeper layers (80–140 cm), equal to 47 mm soil water storage. Roots were concentrated to the upper 140 cm of the soil profile. At maturity in 1994, 90% of the roots were concentrated in 0–80 cm and 96% in 0–140 cm. At flowering in 1995, 84% of the roots were found in 0–80 cm and 95% in 0–140 cm. Roots were observed down to 240 cm in 1994 and 220 cm in 1995 (root length densities below 0.1 cm cm^{-3}). Based on this data and neutron probe data on the advancement of the wetting front, we have assumed a soil water extractable soil profile of 0–80 cm for GP1 and 0–140 cm for GP2 and GP3. The thresholds of PWP + 0.03 m^3 m^{-3} for the upper soil profile (0–60 cm) and PWP + 0.04 m^3 m^{-3} for 60–140 cm were used as indicators

Table 1. Grain yield, biomass, harvest index (HI), yield components and cumulative rainfall for GP1–GP3 during the three rainy seasons 1994–1996. Cumulative rainfall for GP 1 (0-40 DAS), GP 2 (41–80 DAS) and GP 3 (81–110 DAS)

Year		Growth Phase 1			Growth Phase 2		Growth Phase 3				
		Rainfall (mm)	Hills 100 m^{-2}	Panicles hill^{-1}	Rainfall (mm)	Nb Grain pan^{-1}	Rainfall (mm)	Grain mass (mg)	Grain yield (kg ha^{-1})	Biomass[a] (kg ha^{-1})	HI (%)
1994	Mean	81	92.4c[b]	2.82ab	231	2158b	284	8.85a	512a	2340b	18b
	SD[c]		7.4	0.74		562		0.89	180	848	1.6
1995	Mean	154	98.1a	3.00a	294	2586a	69	7.60b	543a	2270b	20a
	SD		2.4	0.53		560		0.80	166	781	1.8
1996	Mean	140	95.1b	2.65b[d]	92	1894b	256	8.69a	429b	2813a	16c
	SD		3.9	0.41		448		0.99	126	883	4.0

[a] Total dry matter of above ground biomass.

[b] Means followed by different letters within each column are significantly different at the 5% level using Student–Newman–Keuls test.

[c] Standard deviation (SD).

[d] Low value explained by the high proportion of sterile hills due to water shortage during GP2 – Nb pan. hill^{-1} of fertile hills = 2.94 pan. hill^{-1}.

Table 2. Development of LAI during the 1994 (above) and 1995 (below) rainy seasons for different treatments. Values in italics indicate LAI$_{max}$

	Control			Manure			Fertiliser		
DAS[a]	Mean	SD[b]	Sign.[c]	Mean	SD	Sign.	Mean	SD	Sign.
26	0.004	0.002	b	0.007	0.003	a	0.005	0.002	b
42	0.02	0.01	b	0.04	0.02	a	0.03	0.01	ab
58	0.10	0.07	b	0.16	0.07	ab	0.22	0.10	a
75	*0.36*	*0.20*	*b*	*0.45*	*0.26*	*ab*	*0.63*	*0.26*	*a*
89	0.32	0.14	b	0.41	0.12	ab	0.52	0.19	a
104	0.09	0.06	c	0.15	0.06	b	0.24	0.11	a

	Control			Manure			Fertiliser		
DAS	Mean	SD	Sign.	Mean	SD	Sign.	Mean	SD	Sign.
24	0.010	0.005	b	0.015	0.004	ab	0.017	0.006	a
38	0.05	0.02	b	0.11	0.05	a	0.13	0.04	a
51	0.19	0.08	b	0.33	0.11	a	0.44	0.16	a
65	*0.44*	*0.11*	*b*	*0.66*	*0.17*	*a*	*0.76*	*0.16*	*a*
79	0.26	0.10	b	0.33	0.10	b	0.47	0.11	a
94	0.11	0.05	b	0.13	0.05	b	0.23	0.08	a

[a] Days after sowing (DAS).

[b] Standard deviation (SD).

[c] Different letters along a row indicate significantly different mean LAI (at the 5% level) using the Student–Newman–Keuls test.

of the water content below which the crop starts to experience water shortage. This range of 0.052–0.071 m^3 m^{-3} coincides well with soil water thresholds used by Payne et al. (1991) for millet trials in Niger, and corresponds to a soil water storage of 54 mm for 0-80 cm and 97 mm for 0–140 cm.

Rainfall distribution and soil water storage for the three rainy seasons are presented in Figures 2 and 3. Growth phases are distinguished, covering 0–40 DAS for GP1, 41–80 DAS for GP2 and 81–110 DAS for GP3. As seen from Figure 3, 1994 suffered from an early season drought (GP1) with soil water storage well below 50 mm, whereas in 1995 soil water availability dropped below 100 mm during GP3, indicating a period of shortage. In 1996, a mid-season dry spell hit the crop during GP2.

Year effect of water shortage

Table 1 presents grain yield, above ground biomass, and yield components of the main subplots, averaging all slope positions and fertiliser treatments. It also shows the cumulative rainfall for each growth phase. Grain yield attained normal levels all years. This is a result of a normal rainfall pattern with close to average cumulative rainfall and a bad distribution causing a short dry spell each year. No correlation can be found between annual rainfall and yield. The early season dry spell in 1994 caused a significant loss of hills compared to both 1995 and 1996, and a low number of panicles. Yet, because of excellent water availability during GP2 and especially in GP3, the relatively few grain were well filled. Good rainfall distribution during panicle initiation and flowering in 1995 resulted in significantly higher number of hills, panicles and grain compared to the other years. Water shortage hit the crop during GP3, which resulted in significantly lower grain mass compared to 1994 and 1996. The mid-season dry spell during 1996 seriously affected flowering, resulting in poor grain formation (27% lower grain number than 1995) and a large proportion of sterile hills; 10% of the hills yielded no grain in 1996, compared to only 0.3% in 1995. Mean panicle number of fertile hills in 1996 amounted 2.94 panicles hill^{-1}

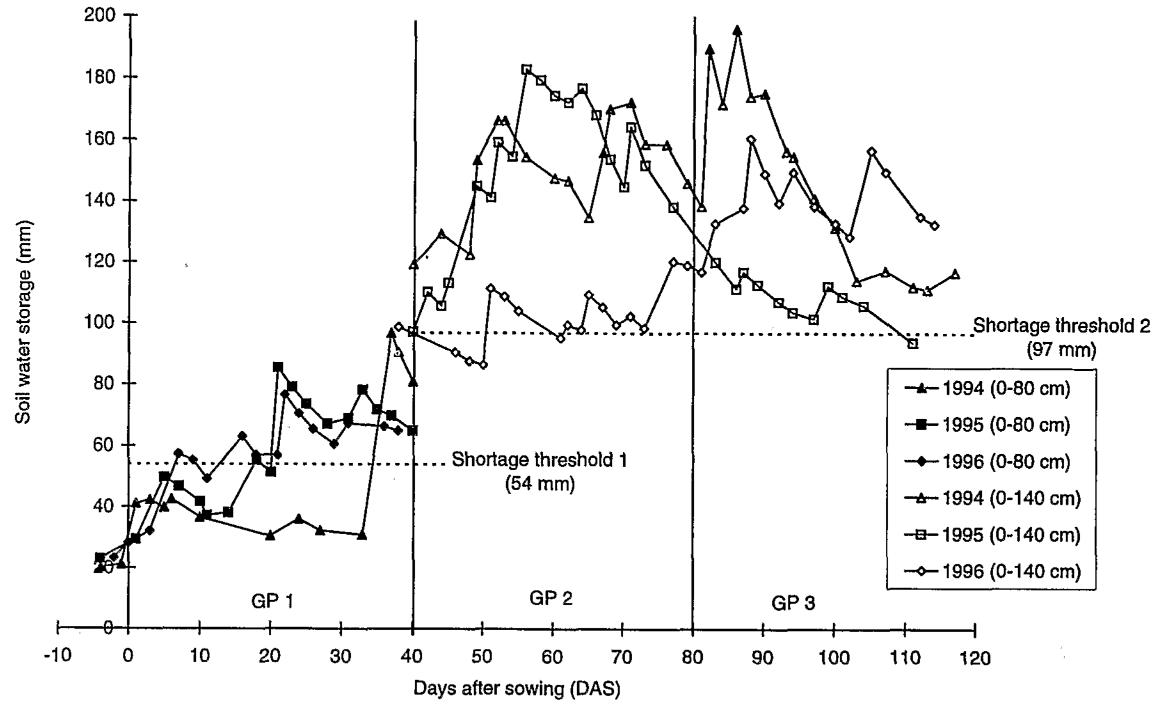

Figure 3. Development of soil water in the root zone (0–80 cm during GP1 and 0–140 cm during GP2 and GP3) for the three rainy seasons (1994–1996). Thresholds indicating soil water shortage are shown with dotted lines (54 mm for GP1, and 97 mm for GP2 and GP3).

which indicates that many panicles were initiated during the favourable soil water conditions during GP1. That 1996 was a favourable growing season except for GP2 is also manifested in high above ground biomass and subsequent low harvest index (HI). Table 1 indicates that the relative performance of a yield component was determined by rainfall availability during the growth phase when it is formed. It also indicates that bad performance of a yield component due to a dry spell can be compensated for by other components in periods of favourable rainfall.

Rainfall distribution and leaf area

Figure 4 presents the soil water storage (0–80 cm) for two contrasting rainy seasons, 1994 and 1995, based on the mean storage for the entire field, and mean LAI for all treatments during the same period. The water shortage of 1994 (DAS 15–33), had a strong influence on leaf area, compared to 1995. The full expansion of leaves was delayed which prolonged the whole growing cycle. The displacement of the 1994 LAI curve, with approximately the same time period (15 days) as the soil water curves, followed the seasonal water availability. The water shortage which impeded leaf growth also delayed the initiation of tiller buds and the subsequent emergence of stems. Maximum leaf area was also affected, attaining only 0.50 m^2 m^{-2} compared to a maximum of 0.66 m^2 m^{-2} in 1995. The rapid drop of the 1995 LAI curve (Figure 4) reflects the deficit of water during the end of the growing cycle (80–110 DAS). This water shortage resulted in an accelerated drying and shedding of leaves, with less leaves left to sustain the process of grain filling, hence the low grain mass (Table 1).

There are no statistically significant differences in LAI between slope positions. LAI data for different treatments is presented in Table 2. Timing of maximum LAI (LAI_{max}) is determined by rainfall distribution and not by treatment. For both years LAI of NP_{fert} millet was significantly higher compared to control (1994) and to both manure and control (1995), when the whole population is analysed. LAI_{max} is low, only 0.76 m^2 m^{-2} in 1995. In 1996, LAI_{max}= 0.92 (DAS 79) for NP_{fert} millet. LAI_{max} for control was merely 0.44 m^2 m^{-2} in both 1995 and 1996. The effect of manure on leaf growth was reinforced over the years, with LAI_{max} increasing from 0.45 m^2 m^{-2} to 0.86 m^2 m^{-2}

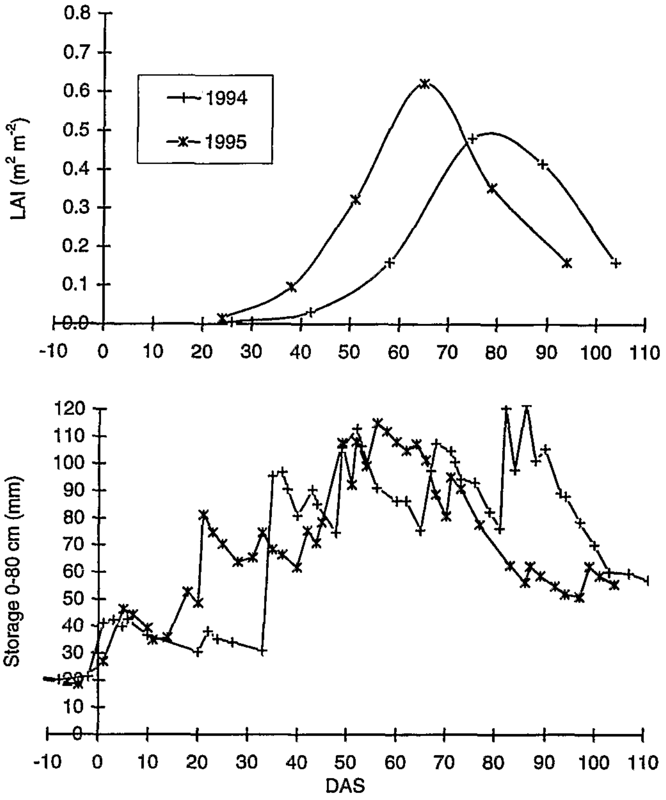

Figure 4. Development of mean LAI (control and NP_{fert}) and soil water storage (0–80 cm) 1994–1995. Soil water data calculated as mean storage for all access tubes in control and NP_{fert} plots (total 24 tubes).

(an increase of 91% compared to 46% for NP_{fert} millet). The increase of LAI_{max} from 1994 to 1995 was similar for both control (22%) and NP_{fert} crop (21%), which indicates that there was no specific nutrient response on leaf growth during the year with favourable soil water during GP1–GP2 (1995), when analysing the entire field.

Soil water, yield and yield components along the slope

The development of soil water storage in 1994 and 1995 for the three slope positions during GP1 is presented in Figure 5. During both years there is a tendency towards a slower increase in rootzone soil water for the upslope position compared to both mid- and downslope positions, which is especially manifested during the period of water shortage in 1994. Figure 6 shows the difference in soil water increase between the upslope and the downslope positions in 1994. Downslope, soil water availability in the root zone was between 5–7 mm higher than upslope, during the emergence of the crop. The difference declined progressively during the period of water shortage, as a result of plant extraction and soil evaporation, to around 2 mm at the moment of the rainfall event on DAS 34 which ended the dry spell. Thereafter, the difference between downslope and upslope tended to increase progressively, levelling off at around 25 mm at the moment of harvest (indicated by the regression line in Figure 6).

The effect of slope position on yield components is reinforced during periods of water shortage (Table 3). The water shortage in 1994 during panicle initiation was experienced more severely by the upslope crop (2.67 pan. $hill^{-1}$) than downslope (2.99 pan. $hill^{-1}$). The late season dry spell in 1995 did more damage upslope than downslope (7.05 versus 7.68 mg $grain^{-1}$). Grain number upslope 1996, caused by the mid-season drought, was significantly (at the 5% level) lower than downslope (1468 versus 2140 grains $pan.^{-1}$). Mean values for yield components showed a high variation between years (difference of 0.33 pan. $hill^{-1}$, 704 grain $pan.^{-1}$, 1.26 mg $grain^{-1}$). For each year the yield com-

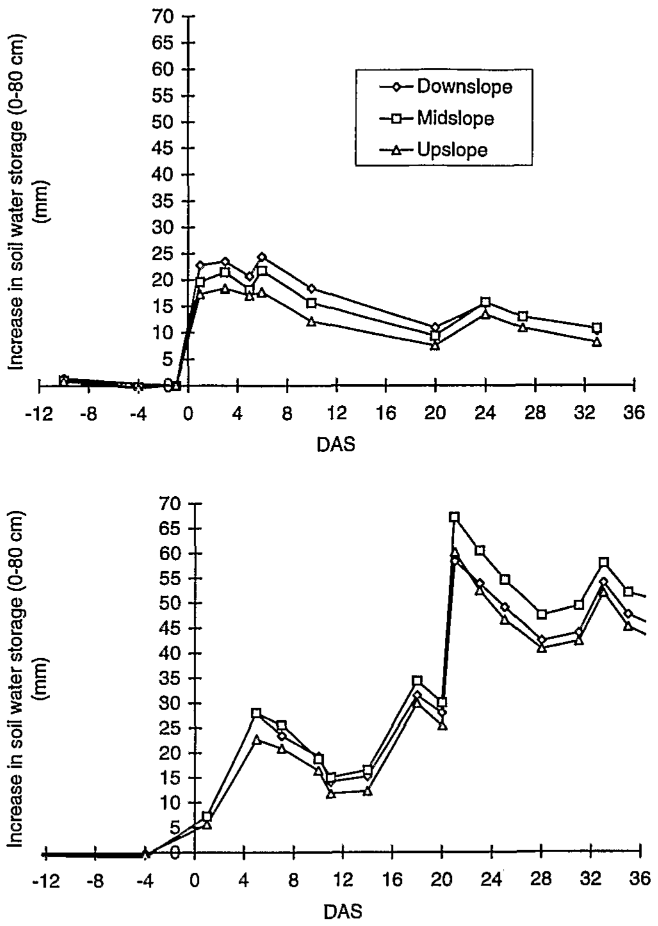

Figure 5. Comparison of early season soil water storage (0–80 cm) at different slope positions for 1994 (water shortage during GP1) and 1995 rainy seasons (no shortage during GP1).

Table 3. Grain yield, Harvest index (HI) and yield components for slope positions 1994–1996

	Hills 100 m^{-2}			Pan. $hill^{-1}$			Nb grain $pan.^{-1}$			Grain mass (mg)			Grain yield (kg ha^{-1})			HI (%)		
Position	1994	1995	1996	1994	1995	1996	1994	1995	1996	1994	1995	1996	1994	1995	1996	1994	1995	1996
Upslope	93.4ab	98.0b[a]	93.7b	2.67b	2.77b	2.87b	2230b	2563b*	1468b	8.18b	7.05b	8.33b*	468b	470b	335b	0.17b	0.19b	0.14b
Midslope	88.3b	97.6b*[b]	95.7b	2.80b	3.04b	2.60b	2327b	2604b*	2038a	8.67b	8.03a	8.96b*	518b	564b	472a	0.18ab	0.20b	0.16ab
Downslope	95.3a	98.8b*	96.0b	2.99b	3.18b	2.52b	1916b	2591b*	2140a	9.70b	7.68a	8.78b*	550b	596b	481a	0.19a	0.20b	0.18a

[a] Test of slope effect: mean values within a column followed by different letters are significantly different at the 5% level using Student–Newman–Keuls test.

[b] Test of the effect of water shortage: *indicates a significant difference (at the 5% level using Student–Newman–Keuls test) within a row, in relation to the year with water shortage for each slope position (Hills 100 m^{-2} – test if 1995>1994; Nb grain – test if 1995>1996; grain mass – test if 1996>1995).

ponent most affected by water shortage (1994 – hill establishment, 1995 – grain mass, 1996 – grain number) was significantly (at the 5% level) lower for all slope positions (except upslope hills 100 m^{-2} 1994) compared to the most favourable year (1995 > 1994 for hill 100 m^{-2}, 1995 > 1996 for grain pan^{-1}, 1996 > 1995 for grain mass). As yield components can compensate for each other during years with periodic water shortage, the inter-annual variation of mean yield amounted to only 114 kg ha^{-1}. Compared to the

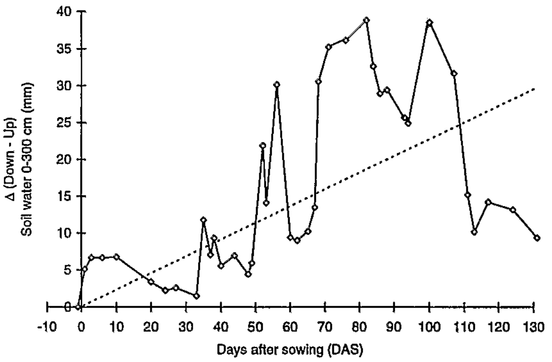

Figure 6. Difference in soil water storage between downslope and upslope positions 1994 and 1995. Data calculated as the difference between mean values of soil water storage (8 tubes per slope position).

Table 4. Slope coefficients (k) and intercepts (m) from linear regression analysis of grain yield data along the slope for control and fertiliser 1994–1996. Regression equation $y = kx + m$ with y=grain yield (kg ha^{-1}) and x=slope position (meters)

	Slope (k)				Intercept (m)			
Year	Control		Fertiliser		Control		Fertiliser	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1994	−0.74b*[a,b]	0.29	−0.90b*	0.47	499.0	78.2	747.7*[c]	153.3
1995	−0.59b*	0.21	−1.33a**	0.40	530.9	96.4	890.1***	44.7
1996	−0.55b**	0.17	−1.05a**	0.26	436.8	61.8	661.9**	84.1

[a] * indicates the strength of rejection of the H0 = 0 hypothesis in Students T-test that slope = 0 (* sign. at the 5% level, ** sign. at the 1% level, *** sign. at the 0.1% level).

[b] Different letters in each row indicate significant differences in slope coefficients (k) between treatments at the 5% level (ANOVA analysis).

[c] * indicate significant differences between treatments for each year (same levels as (1) above) (ANOVA analysis).

seasonal variation of yield components, the variation induced by slope position is low (0.14 pan hill^{-1}, 236 grain pan^{-1}, 0.87 mg grain^{-1}). All yield components upslope are inferior to downslope. Upslope compensation for water shortage is not possible as the effect on yield of yield components is cumulative. The result is a difference in yield between up and downslope of 118 kg ha^{-1}.

Figure 7 shows grain yield (kg ha^{-1}) along the slope from the 19 subplots for control (A) and NP_{fert} (B) treatments during the three rainy seasons. The limit of the last subplot downslope was set to 0 meters, with the last upslope subplot located at 311 meters. The dots show the average yield, from the four replicates, for each slope position. Yield fluctuations along the slope were high, especially in 1994, with SD = 238 kg ha^{-1} for control millet (mean = 385 kg ha^{-1}), and a factor of 46 between minimum (27 kg ha^{-1}) and maximum yield (1249 kg ha^{-1}). High variability is explained by the growing conditions on-farm with a high presence of crusted zones, areas with shrubs, old termite mounds, etc. The high point for control millet in 1994 at 130 meters is, for example, a result of a residual manure effect from an animal enclosure located there two years before the experiment started.

A statistical analysis of the yield data along the slope based on a linear regression model is presented in Table 4. The analysis is done on the slope coefficients (k) and intercepts (m) for regression lines from each series of plots (four control and four NP_{fert} plots with 19 yield data entries for each year). Students T-test was used to analyse the null-hypothesis that the slope coefficients were equal to zero (H0 = 0, i.e. no slope). The k values in Table 4 are the mean coefficients from the four plots for each treatment. The T-test of the k values indicate (at the 5% level) that yields, for all years and treatments, progressively diminish moving up the slope. Slope coefficients of NP_{fert} plots are higher (more negative indicating a stronger slope effect) than control plots (statistically significant only for 1995 and 1996). There is no statistically discernible difference for k values between years. These results suggest that there is a greater benefit from fertilisers applied downslope. Treatment effects were analysed from the intercepts (m) (Table 4). Analysis of variance (ANOVA) indicates significantly higher intercepts for NP_{fert} millet compared to control millet for all years.

Soil water shortage and nutrient deficiency

Table 5 illustrates the interactive effect of nutrient deficiency and water shortage on yield and yield components. Manure favours early growth conditions. This was especially evident during the dry spell in 1994, which resulted in a significantly higher number of hills 100 m^{-2} and superior LAI. Manured millet had systematically intermediate yield to control and NP_{fert} crop. Even though the applied cow dung was poor in plant nutrients, both panicle number and grain mass were higher than the control. Interactions between water shortage and fertiliser application indicate that an early season dry spell (1994) can be partially overcome by fertiliser application (3.38 pan. hill^{-1}). Few rains at the grain-filling stage (1995) caused less suffering in NP_{fert} millet (grain mass 8.3 mg) than in unfertilised plants (grain mass 7.2 mg). The mid-season dry spell

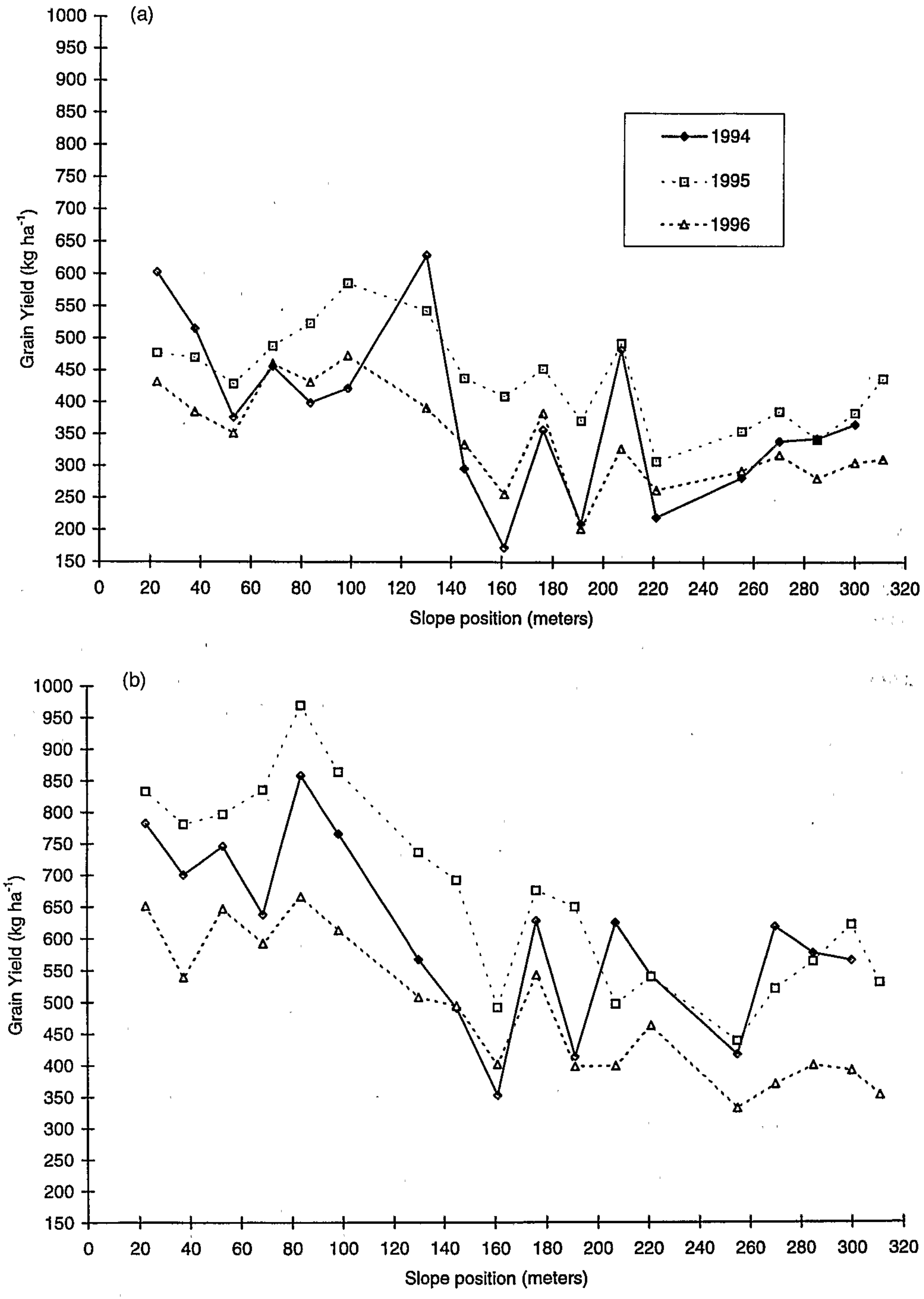

Figure 7. Grain yield (kg ha^{-1}) along the slope 1994-1996. Grain yield is calculated as a mean for replicates of control (A) and NP_{fert}(B) subplots. Slope position set to 0 meters at the downslope limit of the subplots, with upslope plot No. 19 located at 311 meters.

Table 5. Grain yield and yield components for NP$_{\text{fert}}$ (F), manured (M) and unfertilised (C) millet 1994–1996

	Hills 100 m^{-2}			Pan. hill^{-1}			Grain pan.$^{-1}$			Grain mass (mg)			Yield (kg ha^{-1})		
Year	C	M	F	C	M	F	C	M	F	C	M	F	C	M	F
1994	89.6b[a]	97.1a	90.4b	2.40b	2.69b	3.38a	1924b	n/a	2391a	8.7b	8.7b	9.0b	366c	523b	646a
1995	97.1b	98.3b	98.9b	2.59b	2.83b	3.58a	2601b	2616b	2542b	7.2b	7.4b	8.3a	422b	511b	697a
1996	94.0b	95.4b	96.0b	2.33b	2.70b	2.91a	1984b	1769b	1936b	7.8c	8.8b	9.5a	347b	415b	526a

[a] Means values along a row for each year and yield component, followed by different letters are significantly different at the 5% level using Student–Newman–Keuls test.

(1996), however, caused an equal loss in grain number for both fertilised and unfertilised millet. These results indicate that nutrients are more limiting for growth than water during panicle initiation and grain filling, while water constitutes the critical growth factor during flowering and grain formation.

Yield components can be used to identify periods in the millet growing cycle in which water (1) and nutrients (2) alternate in being the limiting factor for growth. This corresponds to two types of graphs.

1. If the yield components of NP$_{\text{fert}}$, manured and control millet are grouped together, forming clouds of points each representing a specific rainfall year, we can conclude that crop performance under a given rainfall regime was not much affected by nutrients because fertilised and control millet reached about equal levels. Instead, it was the seasonal water availability that induced a spread in yield data.
2. The inverse is found if the yield components from different rainfall seasons are concentrated forming groups of NP$_{\text{fert}}$, manured, and control crop. Here we can conclude that, irrespective of rainfall regime, it is the nutrient status that determines crop growth and not water availability. Furthermore, since the results show that downslope position is less vulnerable to dry spells, millet growth should interact with slope position especially during periods of water shortage. In periods when nutrients determine growth, the slope position is not expected to interfere with crop growth because soil fertility is hardly different upslope to downslope.

Figure 8 illustrates the relative importance of water and nutrients by identifying "year (water) groups" (representing (1) above) or "nutrient groups" (representing (2) above), and the impact of slope (opposing downslope to upslope), for the three rainy seasons. Number of hills (Figure 8A) was governed by early rainfall and soil surface conditions. Year-groups (water) were more coherent than nutrients groups, except for the manured plots. The manure probably favoured infiltration, resulting in fewer missing hills, even in the early drought year 1994. Downslope position had less missing hills (0–6%) compared to upslope (1–12%). Nutrient availability had the strongest influence on the number of panicles hill^{-1} (Figure 8B), with NP$_{\text{fert}}$ millet producing a significantly larger number of panicles than unfertilised millet all years (Table 5). The manured plots held an intermediate position due to lower nutrient content than the fertiliser. Within treatment groups, however, 1995 had highest panicle numbers, the early drought year of 1994 was intermediate, and the mid-season drought year of 1996 was worst, as entire hills were rendered sterile. Grain number (Figure 8C) was determined by seasonal rainfall distribution. Mid-season water shortage (1996) affected flowering and subsequently reduced grain number in all treatments, especially upslope. Single grain mass (Figure 8D) was affected by nutrient and water availability. The seasonal impact on grain weight, however, was more pronounced than treatments (it is easier to isolate year groups than nutrients groups). The year of late-season water shortage (1995) affected control and manured millet. Irrespective of timing of the dry spell, downslope millet grain were heavier if fertiliser or manure was applied. In Figure 8E, the resultant grain yield shows that groups are formed by plant nutrient availability. However, within groups, 1995 yielded best, 1996 yielded worst and 1994 was intermediate. Fertiliser application was more effective downslope than upslope, with a gain of 80 kg ha^{-1} upslope and 300 kg ha^{-1} downslope for the year with lowest yield levels (1996), and 240 kg ha^{-1} upslope, 375 kg ha^{-1} downslope in the year with highest yields (1995). For manured millet this equalled 10 kg ha^{-1} and 100 kg ha^{-1} in 1996, and 30 and 120 kg ha^{-1} in 1995.

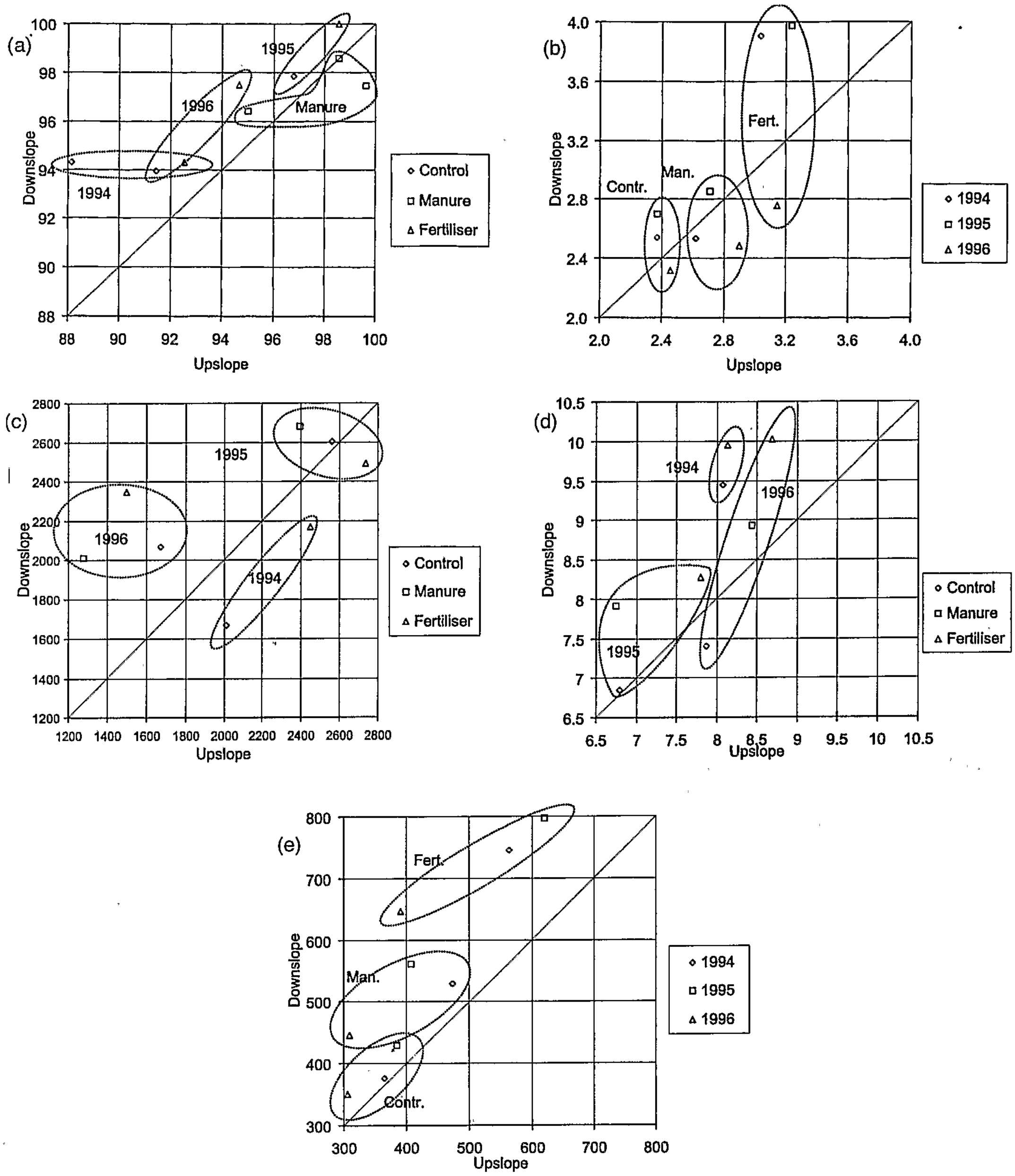

Figure 8. Comparison between upslope and downslope of millet grain yield and yield components for different nutrient treatments (control, manure, fertiliser) and water availability (1994–1996). Figure 8A (hills 100 m^{-2}), 8B (Nb pan. hill^{-1}), 8C (Nb grain pan.$^{-1}$), 8D (single grain mass (mg)), 8E (grain yield (kg ha^{-1}). The scatter plot data is regrouped in "year groups" (indicating the dominating role of water in limiting crop growth) and "nutrient groups" (indicating the dominating role of nutrients in limiting crop growth).

Discussion

Despite the low soil fertility and the dry hydroclimate in this Sahelian on-farm experiment the results indicate the presence of a slope effect on crop productivity. This progressive increase in yields as one moves downslope is more pronounced for fertilised than non-fertilised millet. Over a distance of 300 meters, yields of NP$_{\text{fert}}$ millet increased on average 75% from the upslope to the downslope limit of the field, compared to 62% on average for the non-fertilised millet. Upslope suffered more during periods of water shortage, systematically for all yield components subject to a water shortage (11% lower number of pan. $hill^{-1}$ in 1994, 31% lower grain number in 1996, and 8% lower grain mass in 1995, compared to downslope). Higher soil water availability downslope, as a result of redistribution of surface overland flow, is a contributing factor to these yield gradients. In general, the presence of such a productivity gradient is not considered in agronomic and hydrological research in the Sahel. An explanation to this could be that the soil water gradient is not strong enough to permit a switch in crops, i.e. millet is cultivated on all sandy soils. This in contrast to more humid regions in West Africa where pearl millet is grown on the degraded uplands, sorghum on mid-slopes, and maize and sorghum on the soil water rich lower slopes down to the lowlands (Stoop, 1986, 1987; van Staveren and Stoop, 1985). The slope variability observed here favours a flexible response to water shortage, enabling the crop to escape from periods of drought. Field scale variability and toposequence effects on crop growth can, therefore, be seen as a strategic part of the Sahelian farmer's efforts towards risk reduction, rather than solely as an obstacle to yield increases. Spatial variability can also be exploited in favour for increased crop production, as shown for soil properties when using site specific precision farming (Bouma et al., 1995). Low technology precision farming systems, where advantage is taken of field scale variations in soil surface conditions, soil fertility, and spatial variability of soil water, when applying e.g. manure/fertilisers, should be possible to develop in rainfed smallholder farming. The results presented here suggest that when farmers have the opportunity to apply manure or fertilisers, slope interaction is such that they should favour lower slope positions. This is however an area in need of further research.

The observed effects on the millet crop of a post-flowering dry spell, with reduced grain mass, and of a dry spell during flowering, with reduced grain number, concur with earlier findings (e.g. Bielers et al., 1993; Mahalakshmi and Bidinger, 1985). However, we did not observe a compensatory tiller production as a response to early season water shortage, as has been reported for millet (Bidinger et al., 1987; Mahalakshmi and Bidinger, 1986). The absence of such an adaptive tiller production, can be explained by the poor nutritional status of the soil, impeding crop investment in new tillers.

A striking observation is the low LAI values observed in a farmer's field, compared to what is generally reported on pearl millet. LAI_{max} normally exceeds 1.5 m^2 m^{-2} (Azam-Ali, 1983; Sivakumar, 1993), and not seldom reaches 2–3 m^2 m^{-2} (Daamen et al., 1995; Sashidhar et al., 1986), with a maximum of at least 2 m^2 m^{-2} reported for water stressed plants (Squire, 1979). However, there are reports on low LAI values, with $LAI_{max} < 1$ m^2 m^{-2}, for traditional millet crops (Daamen et al., 1995; Wallace et al., 1990). Low LAI can often be explained by the sparse cropping of the farmers, who cultivate with approximately 4500–6500 hills ha^{-1}, compared to common densities of 30,000 hills ha^{-1} in on-station trials. The observations indicate a correlation between rainfall distribution and the performance of yield components, and a timing of leaf growth to soil water availability. Support for such a linkage between LAI, water availability and crop development, can be found in earlier work showing the strong correlation between LAI and pearl millet transpiration (Azam-Ali, 1983; Wallace et al., 1990).

The application of manure probably facilitates hill establishment by its mechanic effect of protecting the soil against wind and water erosion. Support for this is found not only in an increased number of hills (Table 5) but also in a significantly higher LAI for the manure treatment compared to both control and NP_{fert} millet during the early season dry spell in 1994 (and also during GP1 1996). Later in the growing cycle, as some nutrients are made plant available, the manure can contribute to increase panicle number and single grain weight (compared to the non-fertilised crop). In general, application of manure smoothes the slope effect, in contrast to the use of fertilisers which reinforces the importance of the slope. This indicates that the primary need upslope is soil surface management in order to maximise infiltration, and that the primary need downslope is managing plant nutrients. The inertia of the control yields for both water shortage and non-shortage conditions, illustrated in the Figures 8A–E, has been reported earlier for example, by Pichot et al. (1981). In this long-term trial, strongly fertilised sorghum presented high fluctuations in yield between moist years and years with periods of drought, as nutrients never were a limiting factor. For the crop receiving no nutrients the grain yield stabilised at a low level (around 150 kg ha^{-1}), and stayed relatively stable irrespective of rainfall fluctuations. Our results concur with the above, with the addition that the slope effect (i.e. the effect of surface runoff redistribution along the slope) is tuned down by nutrient deficits (a weaker yield gradient along the slope for control millet in our trials).

Nutrient deficiency in the Sahel is often the primary limiting factor for crop growth (Hafner et al., 1993; Klaij and Vachaud, 1992; Powell and Fussell, 1993), and water/nutrient interactions are such that water supply cannot be managed without managing soil fertility constraints (Payne et al., 1992). Our findings give a further insight into the on-farm complexity of these interactions. If analysed on a yearly basis, the results indicate that primarily nutrients and not water determine final yield. But if analysed on the basis of yield components the results suggest that water and nutrients interact during each growth phase, for all fertility levels. The cumulative effect of these nutrient and water interactions is final yield. In 1994, the year with water shortage during GP1, NP_{fert} millet had higher number of hills and significantly higher number of panicles, compared to non-fertilised millet, i.e. a clear nutrient effect. But, under conditions without water shortage (1995), both these yield components increased – with the same percentage for both NP_{fert} and non-fertilised crop – indicating a water effect. The same is observed for single grain mass where NP_{fert} crop had significantly higher grain mass than the control, in 1995 when water shortage was during GP3. But in 1994, with favourable soil water conditions, grain mass increased for all treatments. These results suggest that nutrients play a decisive role in the performance of a growth phase, but that it is only in combination with favourable soil water conditions that a yield component can achieve superior growth. Our results suggest that there might be one exception to the above, and that is grain number. For both 1995 and 1996, grain number was similar for the non-fertilised and the fertilised crop. In 1996 grain number dropped systematically for all three treatments (on average with 27%), due to water shortage during flowering.This indicates that fertilised millet suffers less from early (1994) and late (1995) season dry spells because more biomass, leaves, roots, and tillers are produced to sustain production. The mid-season drought in 1996 affected the pollination of a whole generation of flowering panicles. Only early or late flowering panicles could successfully set seed. The above is in line with earlier findings that grain yield is most sensitive to water shortage during flowering (Doorenbos and Kassam, 1979; Mahalakshmi and Bidinger, 1985). The capacity of the crop to compensate for poor growth during certain growth phases, makes it difficult to analyse the role of water, during years of intermittent droughts, based only on the seasonal end products – cumulative rainfall and yield.

The yield levels reported in this study (means varying between 350–700 kg ha^{-1}), correspond well with average on-farm yields reported in the region. Cumulative rainfall was close to the long-term average, but every year included a period of water shortage affecting yield components. Our yield data, thus, internalise the effect of poor performance of yield components caused by short drought periods, which also probably is the case for much of the yield data reported in the region. This implies that there is an untapped potential for yield enhancement if drought periods can be mastered. An interesting option is the development of runoff farming systems – in order to increase upslope infiltration of rainfall, and water harvesting systems including storage of water – in order to enable supplementary irrigation during periods of droughts.

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References

Azam-Ali S N 1983 Seasonal estimates of transpiration from a millet crop using a porometer. Agr. Meteorol. 30, 13–24.

Bationo A, Christianson C B, Baethgen W E and Mokwunye A U 1992 A farm-level evaluation of nitrogen and phosphorus fertilizer use and planting density for pearl millet production in Niger. Fert. Res. 31, 175–184.

Begg J E 1965 The growth and development of a crop of bulrush millet (*Pennisetum typhoides* S. & H.). J. Agr. Sci. 65, 341–349.

Bidinger F R, Mahalakshmi V and Rao G D P 1987 Assessment of drought resistance in pearl millet [*Pennisetum americanum* (L.) Leeke]. I. Factors affecting yield under stress. Aust. J. Agr. Res. 38, 37–48.

Bieler P, Fussell L K and Bidinger F R 1993 Grain growth of *Pennisetum glaucum* (L) R. Br. under well-watered and drought-stressed conditions. Field Crop Res. 31, 41–54.

Bouma J, Brouwer J, Verhagen A and Booltink H W G 1995 Site specific management on a field level: high and low tech approaches. *In* Eco-Regional Approaches for Sustainable Land Use and Food Production: Proceedings of a Symposium on Eco-Regional Approaches in Agricultural Research, 12–16 December 1994, ISNAR, The Hague. Eds. J Bouma, A Kuyvenhoven, B A M Bouman J and C Luyten. pp 453–474. Kluwer Academic Publishers, Dordrecht.

Breman H and Kessler J-J 1995 Woody plants in Agro-Ecosystems of Semi-Arid Regions. Springer-Verlag, Berlin. 340 p.

Christiansson C B, Bationo A, Henao J and Vlek P L G 1990 Fate and efficiency of N fertilizer applied to millet in Niger. Plant Soil 125, 221–231.

Daamen C C, Simmonds L P and Sivakumar M V K 1995 The impact of sparse millet crops on evaporation from soil in semi-arid Niger. Agr. Water Manage. 27, 225–242.

de Rouw A, Rajot J-L and Schmelzer G 1997 Effets de l'apport de bouses de zebus sur les composantes du rendement du mil (*Pennisetum glaucum* (L.) R. Br.), les mauvaises herbes et l'encroutement superficiel du sol (Niger). *In* La Gestion des Systemes de Culture. Eds. A Milleville et P Biarnes. Editions ORSTOM Colloques et Seminaires, Paris, France. *(In press)*.

Doorenbos J and Kassam A H 1979 Yield Response to Water. FAO Irrigation and Drainage paper No. 33. FAO, Rome. 193 p.

Estèves M and Lenoir P 1994 Un exemple de fonctionnement hydrologique dans la région de Niamey: le basin de Sama Dey. *In* Xème Journées hydrologiques de l'ORSTOM, Montpellier, 13–14 sept. 1994. Colloques et Séminaires, ORSTOM édition, Paris.

Falkenmark M and Rockström J 1993 Curbing rural exodus from tropical drylands. Ambio 22, 427–437.

Fussell L K, Pearson G J and Norman M J T 1980 Effect of temperature during various growth stages on grain development and yield of pearl millet [*Pennisetum americanum* (L.) Leeke]. J. Exp. Bot. 31, 621–633.

Gregory P J and Squire G R 1979 Irrigation effects on roots and shoots of pearl millet. Exp. Agr. 15, 161–168.

Hafner H, George E, Bationo A and Marschner H 1993 Effect of crop residues on root growth and phosphorus acquisition of pearl millet in an acid sandy soil in Niger. Plant Soil 150, 117–127.

Ibrahim Y M, Marcarian V and Dobrenz A K 1985 Evaluation of drought tolerance in pearl millet (*Pennisetum americanum* (L.) Leeke) under a sprinkler irrigation gradient. Field Crop Res. 11, 233–240.

Kassam A H and Kowal J M 1975 Water use, energy balance and growth of Gero millet at Samaru, northern Nigeria. Agr. Meteorol. 15, 333–342.

Klaij M C and Vachaud G 1992 Seasonal water balance of a sandy soil in Niger cropped with pearl millet, based on profile moisture measurements. Agr. Water Manage. 21, 313–330.

Lal R 1991 Current research on crop water balance and implications for the future. *In* Soil Water Balance in the Sudano–Sahelian Zone (Proc. Int. Workshop, Niamey, Niger, February, 1991). Eds. M V K Sivakumar, J S Wallace, C Rénard and C Giroux. pp 31–45. IAHS publication No. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.

Lambert C 1983 Influence de la précocité sur le développement du mil (*Pennisetum typhoides* Stapf & Hubb.) en conditions naturelles. I. Elaboration de la touffe. Agronomie Tropicale 38 (1), 7–15.

Landais E and Lhoste P 1993 Systemes d'élevage et transfert de fertilité dans la zone des savanes africaines. Cahiers Agriculture 2, 9–25.

Le Barbé L and Lebel T 1997 Rainfall climatology of the HAPEX-Sahel region during the years 1960–1990. J. Hydrol. 188/189, 14–43.

Mahalakshmi V and Bidinger F R 1985 Water stress and time of floral initiation in pearl millet. J. Agr. Sci., Camb. 105, 437–445.

Mahalakshmi V and Bidinger F R 1986 Water deficit during panicle development in pearl millet: yield compensation by tillers. J. Agr. Sci., Camb. 106, 113–119.

Mahalakshmi V, Bidinger F R and Rao G D P 1988 Timing and intensity of water deficits during flowering and grain-filling in pearl millet. Agron. J. 80, 130–135.

Maiti R K and Bidinger F R 1981 Growth and development of the pearl millet plant. ICRISAT Research Bulletin No. 6. ICRISAT, Patancheru, India. 14 p.

Matlon P J 1990 Improving productivity in sorghum and pearl millet in semi-arid Africa. Food Research Institute Studies 22 (1), 1–43.

McIntire J and Fussell L K 1989 On-farm experiments with millet in Niger: crop establishment, yield loss factors and economic analysis. Exp. Agr. 25, 217–233.

Nicholson S E 1981 The nature of rainfall fluctuations in subtropical West Africa. Monthly Weather Review 108, 473–487.

Ong C K and Monteith J L 1984 Response of pearl millet to light and temperature. Field Crop Res. 11, 141–160.

Parr J F, Stewart B A, Hornick S B and Singh R P 1990 Improving the sustainability of dryland farming systems: A global perspective. *In* Dryland Agricultural Strategies for Sustainability. Eds. R P Singh, J F Parr and B A Stewart. pp 1–8. Advances in Soil Science, vol. 13. New York.

Payne W A, Wendt C W, Hossner L R and Gates C E 1991 Estimating pearl millet leaf area and specific leaf area. Agron. J. 83, 937–941.

Payne W A, Drew M C, Hossner L R, Lascano R J, Onken A B and Wendt C W 1992 Soil phosphorus availability and pearl millet water-use-efficiency. Crop Sci. 32, 1010–1015.

Payne W A, Hossner L R, Onken A B and Wendt C W 1995 Nitrogen and phosphorus uptake in pearl millet and its relation to nutrient and transpiration efficiency. Agron. J. 87, 425–431.

Pichot J, Sedogo M P, Poulain J F and Arrivets J 1981 Evolution de la fértilité d'un sol ferrugineux tropical sous l'influence de fumure minérales et organiques. Agronomie Tropicale 36 (2), 122–133.

Powell J M and Fussell L K 1993 Nutrient and structural carbohydrate partitioning in pearl millet. Agron. J. 85, 862–866.

Quilfen J-P and Milleville P 1983 Résidus de culture et fumure animale: un aspect des relations agriculture-élevage dans le nord de la Haute-Volta. L'Agronomie Tropicale 38 (3), 206–212.

Rockström J and Ada L 1993 Diagnostic sur le système agraire du "Zarmaganda Central" (Niger). Memoire finale. Institut National Agronomique Paris-Grignon (INA-PG); Chaire d'Agriculture Comparée et de Développement Agricole, Paris, France. 83 p.

Rockström J 1995 Biomass production in dry tropical zones: How to increase water productivity. *In* Land and Water Integration and River Basin Management. Land & Water Bulletin No. 1. pp 31–49. FAO, Rome, Italy.

Rockström J and Valentin C 1997 Hillslope dynamics of on-farm generation of surface water flows: the case of rainfed cultivation of pearl millet on sandy soil in the Sahel. Agr. Water Manage. 33, 183–210.

Sashidhar V R, Gurumurthy B R, Prasad T G, Udaya Kumar M, Seetharam A and Krishna Sastry K S 1986 Genotypic variation in carbon exchange rate, functional leaf area and productivity in finger millet (*Eleusine coracana* Gaertn.): An approach to identify desirable plant types for higher water use efficiency under rainfed conditions. Field Crop Res. 13, 133–146.

Seybou H 1993 Enquête sur les Systemes de Culture, Cas du Terroir de Banizoumbou. Memoire de fin d'Etude. Faculté d'Agronomie, Université de Niamey, Niger. 51 p.

Sivakumar M V K 1993 Growth and yield of pearl millet and cowpea in relay and intercrop systems in the Sahelian zone in years when the onset of the rainy season is early. Expl. Agr. 29, 417–427.

Sivakumar M V K, Maidoukia A and Stern R D 1993 Agroclimatology of West Africa: Niger. ICRISAT Information Bulletin No. 5. ICRISAT, Niamey, Niger. 108 p.

Squire G R 1979 The response of stomata of pearl millet (*Pennisetum thyphoides* S. and H.) to atmospheric humidity. J. Exp. Bot. 30, 925–933.

Squire G R, Gregory P J, Monteith J L, Russell M B and Singh P 1984 Control of water use by pearl millet. Expl. Agr. 20, 135–149.

Stoop W A 1986 Agronomic management of cereal/cowpea cropping systems for major toposequence land types in the West African savanna. Field Crop Res. 14, 301–319.

Stoop W A 1987 Adaptation of sorghum/maize and sorghum/pearl millet intercrop systems to the toposequence land types in the north Sudanian zone of the West African savanna. Field Crop Res. 16, 255–272.

Tennant D 1975 A test of a modified line intersect method of estimating root length. J. Ecol. 63, 995–1002.

van Dam J C, Stricker J N M and Droogers P 1994 Inverse method to determine soil hydraulic functions from multistep outflow experiments. Soil Sci. Soc. Am. J. 58, 647–652.

van Staveren J P and Stoop W A 1985 Adaptation to toposequence land types in West Africa of different sorghum genotypes in comparison with local cultivars of sorghum, millet and maize. Field Crop Res. 11, 13–35.

Wallace J S, Roberts J M and Sivakumar M V K 1990 The estimation of transpiration from sparse dryland millet using stomatal conductance and vegetation area indices. Agr. Forest Meteorol. 51, 35–49.

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