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Effect of year and fertilizer on water-use efficiency of pearl millet (*Pennisetum glaucum*) in Niger

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SUMMARY

A comprehensive study was conducted over a 4-year period (1984–87) to evaluate the water use, growth and yield responses of pearl millet (*Pennisetum glaucum* (L.) R. Br.) cv. CIVT grown with and without fertilizer (30 kg P_2O_5 and 45 kg N ha^{-1}) at the ICRISAT Sahelian Centre, Sadoré, Niger. Our study showed significant year and fertilizer effects on the growth and yield of millet at the study site. Observed year effects were primarily due to the variations in the amount and distribution of rainfall in relation to the potential demand for water. During 1984, 1985 and 1987, total rainfall was below the long term average, while in 1986 it was above average. While the onset of rains (relative to the average date of onset) was early from 1984 to 1986, in 1987 the sowings were delayed by as much as 33 days. Of all the four years, the separation between the treatments in the cumulative evaporation is most evident for 1984, which was a drought year with below-average rainfall in all the months from June to September. Cumulative evaporation patterns in 1985 and 1986 were similar because of regular rains and high average rainfall per rainy day from June to October. In 1987, sowings were delayed until 15 July and only 6·9 mm of rainfall was received per rainy day in July. Hence cumulative evaporation was initially low and showed a significant increase only after two significant rain events in early August. There was a large response to fertilizer in all the years as small additions of fertilizer phosphate increased the soluble phosphate in the soil. Fertilizer application resulted in a small increase in water use (7–14%) in all years except 1987. Increased yield due to the application of fertilizer was accompanied by an increase in the water-use efficiency (WUE) in all the four years with the largest increase in 1985. The beneficial effect of fertilizers could be attributed to the rapid early growth of leaves which can contribute to reduction of soil evaporative losses and increased WUE. Over the four seasons, average increase in the WUE due to the addition of fertilizer was 84%.

INTRODUCTION

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is the principal staple food crop in Niger, West Africa. It is the most commonly grown cereal in this country, making up to 90% of the cropped area (Bationo *et al.* 1993). With 22% of the 14 million ha of pearl millet growing areas, Niger is the second pearl millet producer in West Africa after Nigeria (Fussell *et al.* 1987). Despite its importance in the agricultural systems, average yields of millet in Niger have remained low at *c.* 400 kg ha^{-1} over the past two decades. The low productivity of millet is largely due to the harsh environment in which it is grown.

In a review of pearl millet in African agriculture, Spencer & Sivakumar (1987) concluded that rainfall and soils are the major environmental resources that merit a detailed analysis in the efforts to increase millet production. Previous studies on water use of millet in West Africa assumed that water supply is a primary constraint to millet production (Azam Ali *et al.* 1984; Stroosnijder & Hoogmoed 1984). Since the conditions of such studies (Dancette 1971), when high rates of fertilizer were used, are not typical of farmers' conditions, Payne *et al.* (1990) studied the root zone water balance of three low-input millet fields in Niger. They concluded that water supply may not be assumed *a priori* to be a primary production constraint on low input millet fields.

Shortage of water in the semi-arid tropics (SAT) is not simply a consequence of inadequate rainfall. The

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problem for human settlement, and particularly for agriculture, is the seasonal distribution of rainfall (Sivakumar & Wallace 1991) and the rate at which it is lost by evaporation, which is a major component of water balance in all years (Monteith 1991).

Effective use of the low and variable rainfall is dictated by soil type and its physical and chemical properties. Soil physical properties exert a dominant effect on soil water balance, crop production and water-use efficiency, especially in regions prone to water stress (Lal 1991). As Wadleigh *et al.* (1965) pointed out, there are many issues that emanate from the use and abuse of the soil moisture reservoir. The most dominant types of soils in West Africa are coarse-textured soils containing $> 65\%$ sand and $< 18\%$ clay (Swindale 1982). Soils in Niger for example are very sandy with the sand fraction usually exceeding 80%. They occur extensively on flat to undulating topography developed under eolian and alluvial sand. These are some of the conditions in which pearl millet is traditionally grown.

A number of studies have shown that greater water-use efficiency could be achieved through the use of fertilizers. In his classical review on fertilizers and the efficient use of water, Viets (1962) concluded that in most cases when water supply is fixed, any management factor that increases yield will increase water-use efficiency. It should, however, be pointed out that although improvements in yield may be brought about by judicious applications of fertilizer, if crops run out of water towards the end of their life cycle, applications of high levels of nitrogen and phosphorus may in fact promote vegetative growth and depress harvest index. Water × nutrient interaction studies, often conducted under controlled irrigation such as the line source sprinkler irrigation system, provide the answers to such questions. Such studies are, however, difficult to conduct during the rainy season in the SAT due to unpredictable rainfall patterns. One way to overcome this limitation is to repeat the field trials in time and space that allow inclusion of a range of soil climatic conditions to draw valid conclusions.

Hence the objective of this study, conducted at a semi-arid location in Niger over a 4-year period (1984–87), was to evaluate the water use, growth and yield responses of millet cv. CIVT to a recommended rate of fertilizer application (30 kg P_2O_5 and 45 kg N ha^{-1}).

MATERIALS AND METHODS

The experiment was conducted during the 1984–87 rainy seasons at Sadoré, Niger (13° 15′ N, 2° 17′ E) on the experimental farm of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Centre, located 45 km south of Niamey, Niger. The climate of the site is typical of the southern edge of the Sahelian zone, with summer rainfall and high temperatures throughout the year. Daily weather data were collected at the Agrometeorological Observatory located at the experimental farm.

For long term climate characterization of Sadoré, long term climatic data from 1961 to 1990, the most recent climatic normal database, for Niamey, Niger were obtained from the National Meteorological Service of Niger. Analyses reported here are based on 10-day averaging periods of each month, which are commonly used in the Francophone West African countries. Each month is divided into three 10-day periods starting from days 1, 11 and 21 of each month. The last period of each month, which includes all the days to the end of the month, could have either 10 or 11 days, depending on the month, except for February. Decadal average solar radiation, temperatures, relative humidity, and wind speed were used for computing Penman (1948) potential evapotranspiration (PE). Rainfall probabilities were computed as described by Sivakumar *et al.* (1993).

The soils at the site are classified as sandy, siliceous, isohyperthermic Psammentic Paleustalf with 91% sand, 5% silt and 4% clay in the A horizon, with a bulk density of about 1·65 mg m^{-3} (West *et al.* 1984) and have a pH of 4·9 (in 1:1 soil water suspension), CEC of 1·3 cmol kg^{-1}, base saturation of 41·9%, organic carbon content of 0·2% and available phosphorus (Bray-P1) of 3 mg kg^{-1}.

The experiment was sown in a randomized block design with six replications. The individual plot size in all years was 20 × 15 m. There were three treatments: millet grown with no fertilizer (M1); millet grown with fertilizer (M2: 30 kg P_2O_5 and 45 kg N ha^{-1}); and a bare soil (BS) with no crop.

In treatment M2, a basal application of 45 kg ha^{-1} of P_2O_5, as single superphosphate, was made before sowing and calcium ammonium nitrate was applied at *c.* 21 and 45 days after planting to supply a total of 45 kg ha^{-1} of nitrogen. The millet cultivar CIVT was planted in pockets spaced at 1 × 1 m after the receipt of the first sowing rains (defined as a rainfall of at least 20 mm received after 1 May) in each year. Dates of sowing, emergence and harvest of millet during the four years are shown in Table 1. The pockets were thinned to three plants at *c.* 21 days after sowing.

Soil moisture measurements were made in all the plots with a Troxler neutron probe (Troxler Electronic Laboratories Inc, Research Triangle Park, North Carolina 27709, USA) at 7–10 day intervals throughout the growing season from 30–210 cm soil depth at 15 cm intervals. Soil water in the top 30 cm was measured gravimetrically. Soil water contents were presented as average values over the four replications. The estimation of drainage requires accurate values of the hydraulic conductivity. The hydraulic conduc-

Table 1. *Final grain yield (GY), total water use (WU) and water-use efficiency (WUE) of millet grown with and without fertilizer during four years at ISC, Sadoré, Niger*

	No fertilizer			Fertilizer		
Year	GY (kg ha^{-1})	WU (mm)	WUE (kg ha^{-1} mm)	GY (kg ha^{-1})	WU (mm)	WUE (kg ha^{-1} mm)
1984	290	170	1·71	410	193	2·12
1985	460	361	1·27	1570	387	4·06
1986	1210	430	2·82	1690	467	3·62
1987	590	395	1·51	937	381	2·46
Mean		580				
S.E. for treatment		131				
D.F.		5				
S.E. for year		146				
S.E. for year × treatment		206				
D.F.		30				

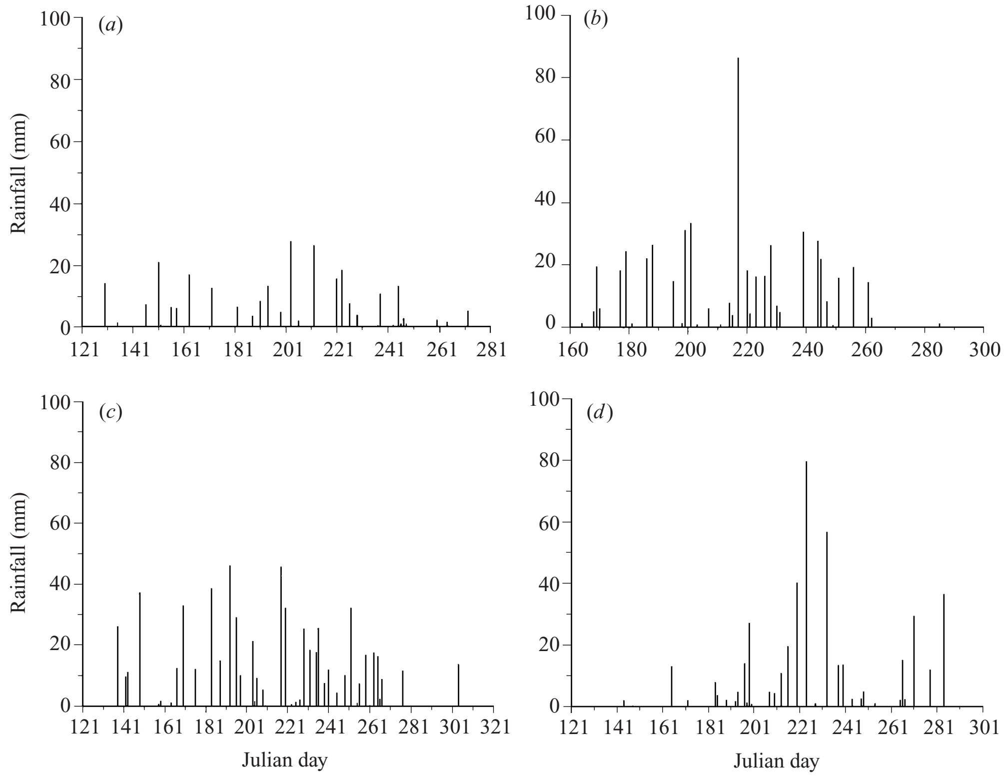

Fig. 1. Rainfall distribution (mm) during (*a*) 1984, (*b*) 1985, (*c*) 1986 and (*d*) 1987 rainy seasons at the ICRISAT Sahelian Centre, Sadoré, Niger.

tivities used here were from the study of Payne *et al.* (1991) which was conducted at N'Dounga, located *c.* 15 km from Sadoré, with soil characteristics similar to those at Sadoré. The details of the method used to estimate drainage from neutron probe data were given by Klaij & Vachaud (1992).

Total water use was computed with a water balance equation (Jensen 1973). Water-use efficiency (WUE) was computed as:

$$\text{WUE} = \frac{\text{Grain yield (kg ha}^{-1}\text{)}}{\text{Total water use (mm)}}$$

Growth measurements were made, in all years except 1986, by sampling whole plants at 7–10 day intervals in a 3 m^2 area in each replicate while ensuring that enough guard area was left around the sampling area. Plants were separated into individual components (i.e. leaves, stems and heads). Leaf area was measured with a leaf area meter (LI-COR Ltd, Lincoln, Nebraska, USA). Plant components were dried to constant weight at 65 °C and then weighed. Natural leaf loss was not included in the final dry matter values. Final yields were obtained from an area of 25 m^2. All results were submitted to an analysis of variance. Yield responses over the four years for the two treatments were analysed using a split-plot analysis.

RESULTS

Inter-annual variability in rainfall

The timing and amount of rainfall received during the four years (Fig. 1) was quite variable and hence provided four distinct and different sets of results. During 1984, 1985 and 1987, total rainfall was below the long term average, while in 1986 it was above average. While the onset of rains (relative to the average date of onset) was early from 1984 to 1986, in 1987 the sowings were delayed by as much as 33 days.

Total rainfall in 1984 (260 mm) was considerably lower than the long term average of 560 mm. Millet established well with moderate rainfall at the end of May and early June, but it suffered severely from drought stress due to low rainfall in August and September. Indeed, 1984 recorded the lowest rainfall amount since 1905 and only three rainfall events during the year produced > 20 mm of rain.

In 1985, the total rainfall of 545 mm was *c*. 4% below the long term average, but was sufficient to allow good crop establishment and vegetative growth. There were several heavy rainstorm events, one of them (on 4 August) giving > 86 mm.

Total rainfall received in 1986 was 657 mm, 17% above the long term average. Except for June, monthly

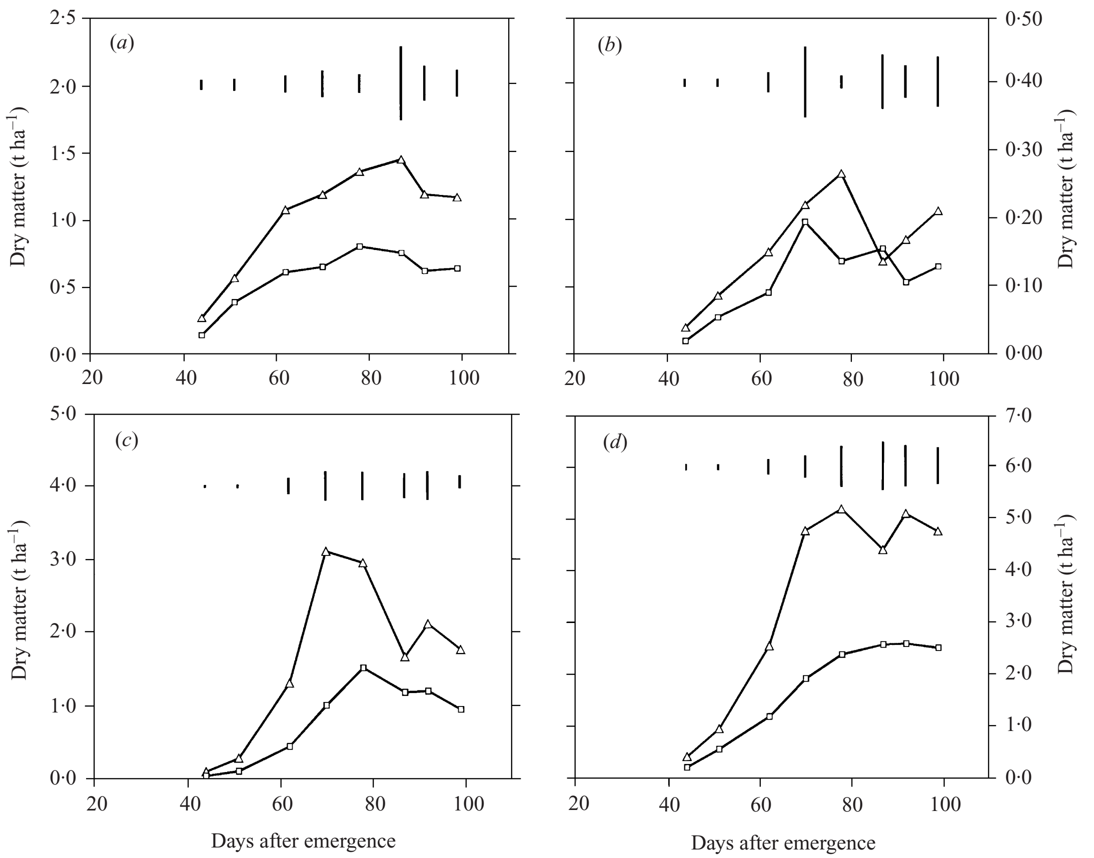

Fig. 2. Dry matter distribution (t/ha^{-1}) in different plant components, (*a*) leaf, (*b*) leaf sheath, (*c*) stem and (*d*) total plant of millet grown with (M2, △), and without (M1, □) fertilizer during the 1984 growing season at the ICRISAT Sahelian Centre, Sadoré, Niger. Vertical bars represent S.E.S (D.F. = 5).

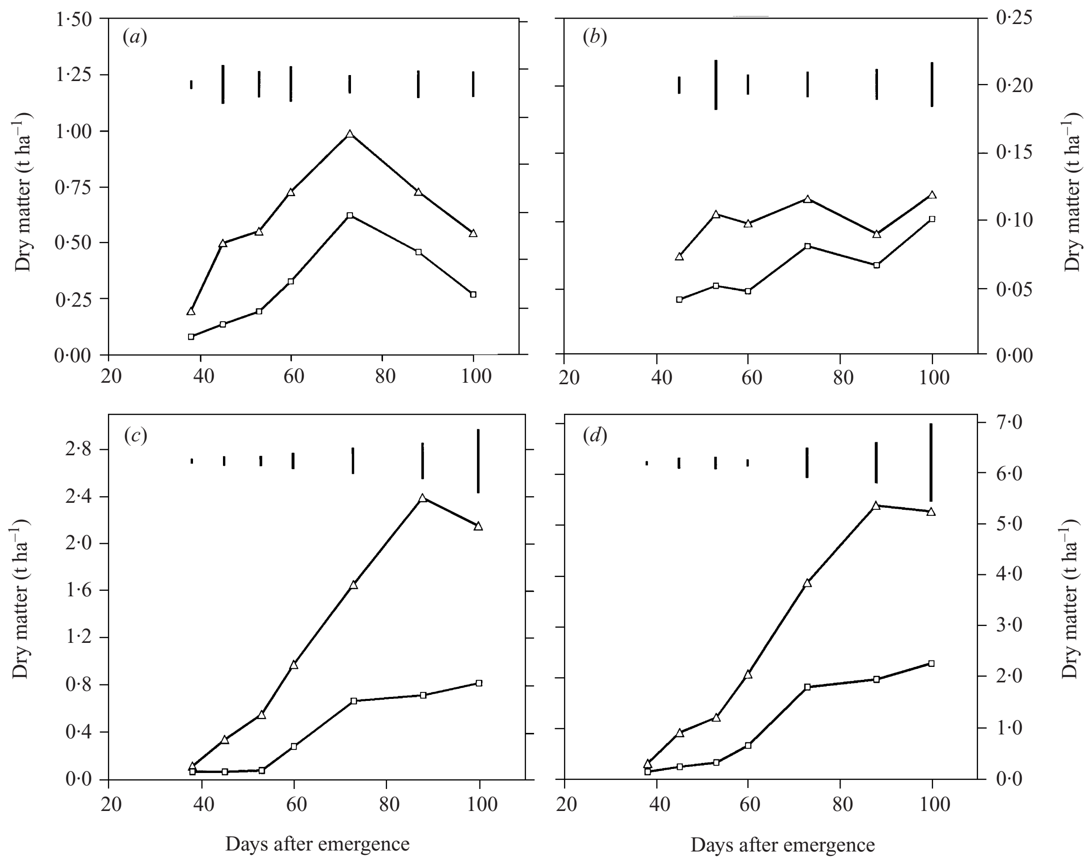

Fig. 3. Dry matter distribution (t/ha^{-1}) in different plant components, (*a*) leaf, (*b*) leaf sheath, (*c*) stem and (*d*) total plant of millet grown with (M2, △) and without (M1, □) fertilizer during the 1985 growing season at the ICRISAT Sahelian Centre, Sadoré, Niger. Vertical bars represent S.E.S (D.F. = 5).

rainfall in 1986 was at or above the long term average from May to October. On seven occasions during the year, the rainstorms recorded more than 30 mm.

The total rainfall of 450 mm in 1987 was 20% below the long term average, but sowings were delayed until 15 July because of lack of sufficient sowing rains. Despite the delayed onset, two rainstorms in August produced 79·5 mm (11 August) and 56·6 mm (20 August), which was 30% of the total rainfall for the year.

Dry matter production and distribution in different components

Dry matter (DM) distribution in millet in different plant components for the M1 and M2 treatments during the 1984 rainy season is shown in Fig. 2. Dry matter accumulation in the leaf, leaf sheath and stem components increased steadily up to 80 days after emergence (DAE) in both the treatments after which there was a decline, specially in the stem component. Millet in treatment M1 produced 2·5 t ha^{-1} of total DM while in treatment M2 it was practically doubled to *c.* 5 t ha^{-1}.

Dry matter accumulation patterns in different plant components in 1985 (Fig. 3), with the exception of the leaf component, did not show the decline in the later part of the growing season as in 1984. However, the treatment response was still similar to that in 1984, with the total DM in treatment M2 reaching 5·4 t ha^{-1} as opposed to 2·3 t ha^{-1} in treatment M1.

In 1987, DM accumulation patterns (Fig. 4) showed a decline quite early in the growing season (i.e. by 58–62 DAE), but showed a recovery later by 82 DAE, specially in the leaf sheath and stem components. The recovery was more dramatic in the total DM component, which includes the head and grain components in addition to the other three components shown in Fig. 4.

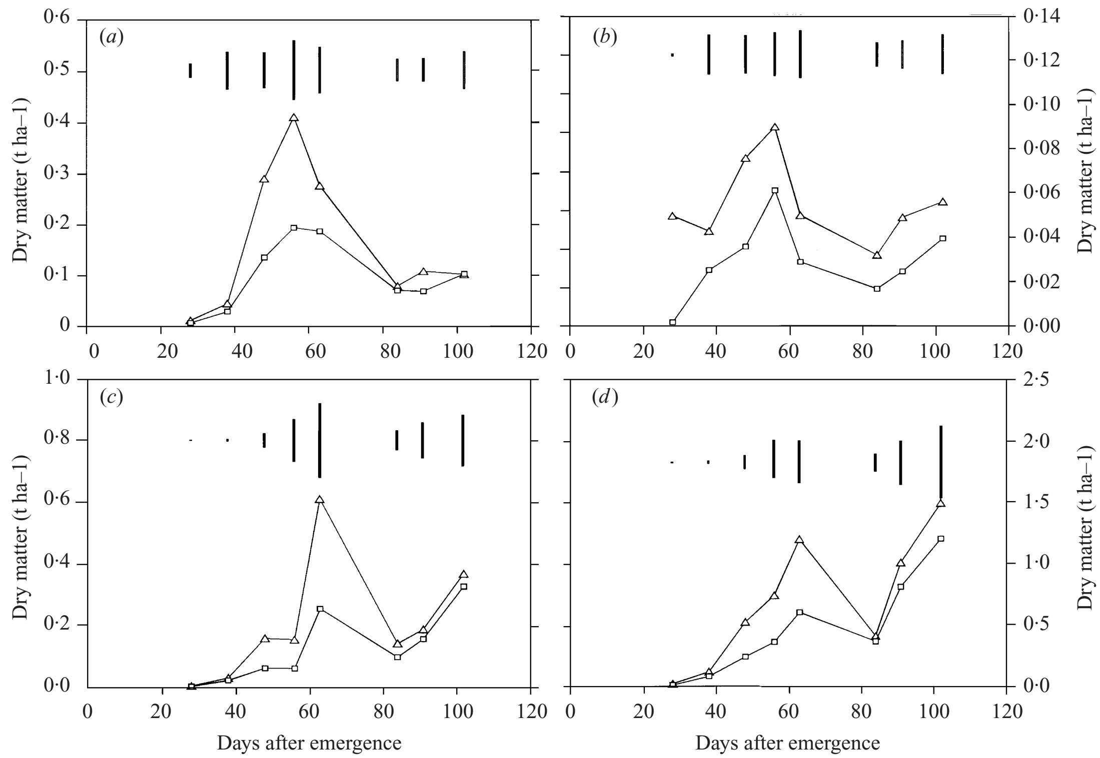

Fig. 4. Dry matter distribution (t/ha^{-1}) in different plant components, (*a*) leaf, (*b*) leaf sheath, (*c*) stem and (*d*) total plant of millet grown with (M2, △) and without (M1, □) fertilizer during the 1987 growing season at the ICRISAT Sahelian Centre, Sadoré, Niger. Vertical bars represent S.E.S (D.F. = 5).

Cumulative evaporation and drainage

Changes in the cumulative evaporation and drainage in the three treatments for the four years are shown in Fig. 5. Total evaporation and drainage in 1984 (Fig. 5*a*) was the lowest in the four years for all three treatments. In 1984, treatments M1 (170 mm) and M2 (193 mm) showed higher total evaporation over the bare soil (BS) treatment which recorded only 105 mm. Drainage was also insignificant in treatments M1 (10 mm) and M2 (7 mm) in comparison with BS (41 mm).

In 1985 (Fig. 5*b*), total evaporation increased significantly in all the three treatments. While treatments M1 and M2 recorded a total evaporation of 361 and 389 mm, respectively, in treatment BS it was much higher and reached 410 mm. Total drainage in treatment M1 was 70 mm in contrast to 38 mm for M2. Treatment BS recorded only 13 mm of total drainage.

Total evaporation was maximum in 1986 (Fig. 5*c*), with 430 mm in M1, 467 mm in M2 and 447 mm in BS. Total drainage was also higher at 90 mm for M1, 63 mm for M2 and 82 mm for BS.

Although the rains started late in 1987, the total evaporation (Fig. 5*d*) was still higher than in 1984 and 1985. Treatment M1 recorded 395 mm of evaporation, while in M2 it was 381 mm with the BS registering 359 mm. Drainage losses in 1987 were lower with only 17 mm for M1 and 19 mm for M2. Treatment BS recorded 31 mm of drainage.

Yield, water use and water-use efficiency

Final grain yield, total water use and water-use efficiency of millet in the two treatments during the four years are shown in Table 1. In all four years, millet showed a significant response to fertilizer, with the yield advantage due to fertilizer application ranging from 39 % in 1986 to 341 % in 1985. There was no significant difference in the total water use between the two treatments in any given year. However, for any given treatment, differences in the total water use across the years were quite large. For example, in 1984 with only 260 mm of total rainfall, water use of millet in treatment M1 was 170 mm and 193 mm in M2. With the above-average rainfall of

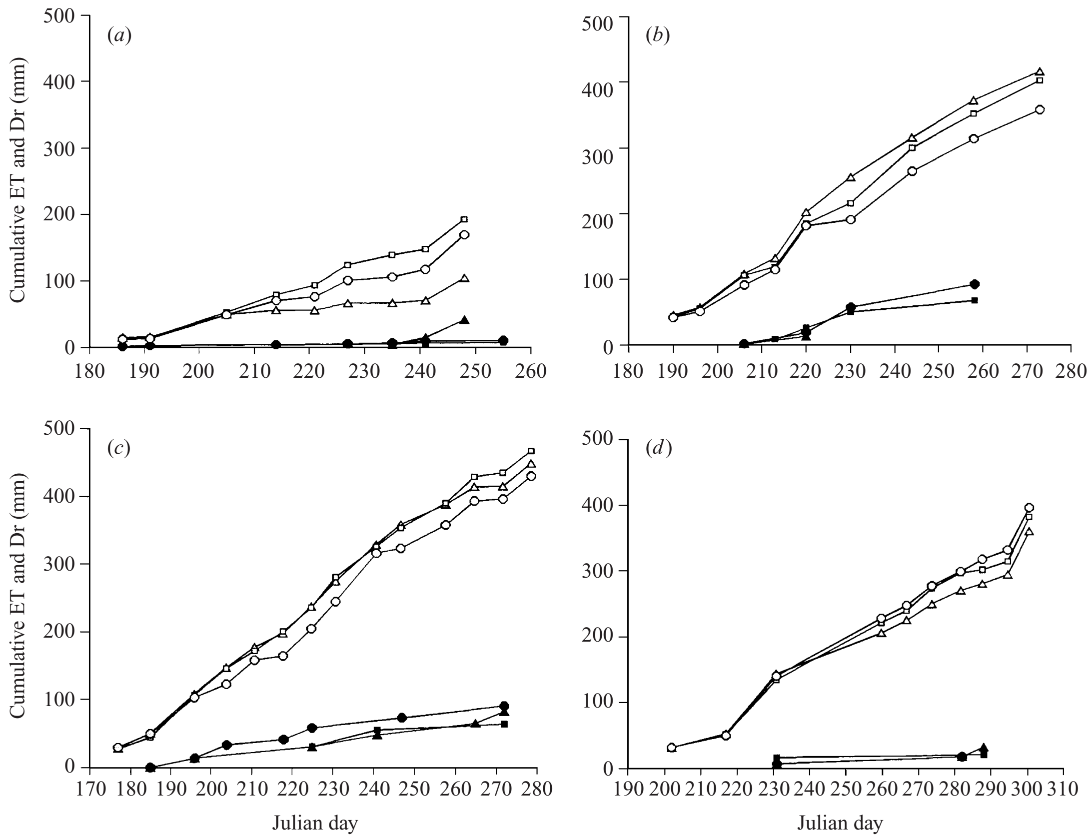

Fig. 5. Changes in the cumulative evaporation (CumEv, ○, □, △) and cumulative drainage (CumDr, ●, ■, ▲) of millet grown with (M2, □, ■) and without (M1, ○, ●) fertilizer and of a bare soil (BS, △, ▲) during the (*a*) 1984, (*b*) 1985, (*c*) 1986 and (*d*) 1987 rainy seasons at the ICRISAT Sahelian Centre, Sadoré, Niger.

657 mm in 1986, millet used substantially more water, 430 mm in M1 and 467 mm in M2. Use of fertilizer increased the water-use efficiency of millet in all the years, with the advantage ranging from 24% in 1984 to 220% in 1985.

DISCUSSION

Pearl millet in the West African Sahel is grown by subsistence farmers with little or no added inputs. Mudahar (1986) reported that the average fertilizer use in Niger is only 0·8 kg ha^{-1} per year. Over the past two decades, the proportion of land under fallows has been decreasing and soils have been continuously mined with a general decline in soil fertility. Under the conditions of low input subsistence agriculture, millet yields are dictated largely by the climatic potential of a location. Our investigation showed significant year and fertilizer effects on the growth and yield of millet at the study site.

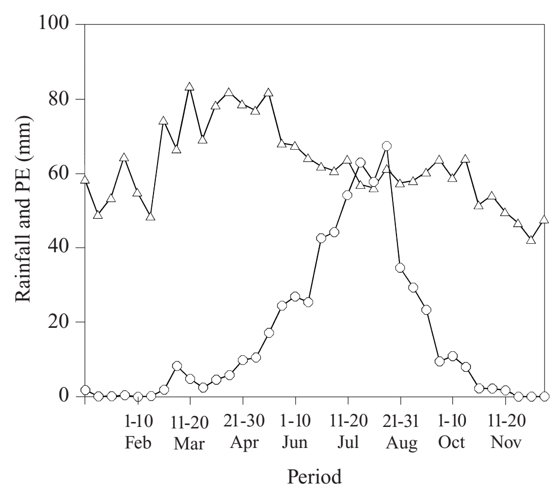

Fig. 6. Average decadal rainfall (○) and potential evapotranspiration (PE, △) patterns for Niamey, Niger.

Observed year effects are primarily due to variations in the amount and distribution of rainfall in relation to the potential demand for water. As shown in Fig. 6, rainfall at Niamey is monomodal and the 10-day average rainfall exceeds potential evapotranspiration for only a short time during the growing season, indicating a great degree of evaporative demand. The probability of receiving 10 mm or more rainfall also shows that at Niamey there is a very long, dry season of about 7 months from November to May and, even when the rains start, the rainfall probability does not reach the dependable level of 75% (Hargreaves 1974) until 21–30 June (Peacock & Sivakumar 1987). Also, the sandy soils at Sadoré with non-plastic wet consistency coupled with weakly coherent massive to subangular blocky structure, promote good permeability. Hence, these soils retain less water and, under high pressure potentials, could drain water rapidly through the soil profile. This stored water could become available for crop growth if it joins up with the wetting front. This implies that good establishment and growth of millet can be favoured by more frequent rains during the growing season that can at least partially meet the continuously high evaporative demand while keeping the rooting zone wet and offer the possibility of a rapid movement of the wetting front towards the stored water. With the high evaporative demand, the efficiency of rainfall storage depends upon the amount of rain per rainy day (Cooper *et al.* 1987). When the rainfall per rainy day is < 5 mm, much of it is often lost through soil evaporation.

A comparison of the rainfall patterns (Fig. 1) and the cumulative evaporation and drainage in the different treatments (Fig. 5) provides some understanding of the year effects. Of all the four years, the separation between the treatments in the cumulative evaporation is most evident for 1984 which was a drought year with below-average rainfall in all the months from June to September. From sowing till 22 July (just before the stage of 50% flowering), rainfall was < 20 mm and average rainfall per rainy day was < 10 mm. Afterwards only two rain events brought > 20 mm of rain (Fig. 1*a*) and total rainfall after 11 August was only 49 mm. Hence, the total evaporation in 1984 was in general low and drainage was negligible. In 1985, however, following the emergence of millet on 22 June until 16 August (when the 50% flowering stage was reached), there were seven rain events with > 20 mm of rain, and one event on 4 August produced 86 mm of rain. Average rainfall per rainy day in July, August and September 1985 was 15·1, 20·7 and 11·8 mm, respectively. In contrast to a total post-flowering rainfall of 74 mm in 1984, 178 mm of rain was received following flowering in 1985. As a result cumulative evaporation was > 360 mm for all three treatments. Cumulative evaporation patterns in 1986 were similar to 1985 because of regular rains and high average rainfall per rainy day from June to October. In 1987, sowings were delayed till 15 July and only 6·9 mm of rainfall was received per rainy day in July. Hence cumulative evaporation was initially low and showed a significant increase only after two rain events of 40 mm and 79·5 mm on 7 and 11 August (Fig. 1*d*).

There was a large response to fertilizer in all the years. The low CEC of Sadoré soils is due to the low organic matter and clay contents. These soils also have a low content of organically bound phosphorus which is a consequence of the low organic matter content. This implies that small additions of fertilizer phosphate would increase the soluble phosphate and give significant crop response. Field trials in Niger have shown that the sufficiency level for P estimated by regression analysis on the basis of Bray-1 extractable P is 7·9 $\mu g\ P\ g^{-1}$ of soil for 90% maximum yield of millet (Bationo & Mokwunye 1991).

Fertilizer application resulted in a small increase in total water use (7–14%) in all years except 1987. It is possible that this could have resulted from increased depth of water extraction (Brown 1971). Under the harsh climatic conditions and sandy soils in Niger, nearly all the plant-available water is used by the crop and since evapotranspiration (ET) losses are largely controlled by meteorological conditions, seasonal ET is nearly the same whether yields are high or low. This could explain the small differences in the observed water use between the treatments.

Increased yield due to the application of fertilizer was accompanied by an increase in the water-use efficiency (WUE) in all four years, with the most dramatic increase in 1985 (Table 1). As Viets (1962) explained, since evapotranspiration is little affected by management, any factor that increases yield will increase WUE. The beneficial effect of fertilizers could be attributed to the rapid early growth of leaves as can be seen from the DM accumulation in the leaf component in all years (Figs 2, 3 and 4). This advantage in the rate of leaf growth conferred by the fertilizer tends to persist until harvest. Similar trends were observed by Gregory *et al.* (1984) and Cooper *et al.* (1987) for barley and wheat under Mediterranean conditions in Syria. Early development of canopy cover helps the crop to intercept more radiation, increase root development and apportion more of the water extracted by the roots to transpiration.

Under the system of pocket planting of millet under wide spacing in the Sahel, soil evaporation losses can be high. Wallace *et al.* (1989), Bley *et al.* (1991) and Fechter *et al.* (1991) showed that direct evaporation from soil in millet can be between 35 and 45% rainfall, the higher proportions occurring in the lower rainfall. Hence strategies such as use of fertilizer, which can promote rapid early growth, can contribute to the reduction of soil evaporative losses and increased WUE. Over the four seasons, the average increase in WUE due to the addition of fertilizer was 84%, which is greater than the 75% increase in WUE due to the use of fertilizer shown by Cooper *et al.* (1987).

The results of our study showed that even at the drier locations in the Sahel, simple management practices such as the application of fertilizer can help to increase the amount of water transpired, thereby contributing to increased productivity. Given the increasing problems of nutrient mining in the Sahel and the growing questions on the sustainability of traditional production systems, the application of a small quantity of fertilizer can be regarded as a simple strategy to ensure productivity and sustainability.

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