Managing Yield and Water Use of Pearl Millet in the Sahel

William A. Payne*

ABSTRACT

Drought occurs often in the West African Sahel, but studies have shown that soil water availability is not usually the limiting factor to pearl millet [*Pennisetum glaucum* (L.) R. Br.] production, and that field water-use efficiency (WUE)—i.e., the ratio of yield to evapotranspiration (ET)—is almost always very low. The purpose of this study was to determine management effects on yield and water use of pearl millet for a range of climate conditions in the Sahel. Grain and aboveground dry matter yield, daily vapor pressure deficit, and soil water data were taken during four years of contrasting rainfall. Within any given year, genotype, plant population, and fertilizer had relatively small to no effect on ET, but large effects on yield. When high plant population (≥20 000 hill ha^{-1}) was combined with high fertilizer application (≥40 kg N ha^{-1} and ≥18 kg P ha^{-1}) during the wettest year, total ET was increased by ≈50 mm. High fertilizer application tended to slightly increase ET and thereby deplete soil water reserves, but this was not associated with yield decline. Yield and water-use data refute the view that, by maintaining fields at low fertility and low plant populations, farmers reduce risk of crop failure during drought by reducing crop water use. Compared with traditional practices that use plant populations as low as 5000 hill ha^{-1} and zero fertilizer input, moderate plant population (10 000 hill ha^{-1}) and fertilizer application (20 kg N ha^{-1} and 9 kg P ha^{-1}) substantially increased yield and approximately tripled WUE even during 1984, the driest year on record. In general, grain yield was better predicted from ET within different management categories when corrections were made for mean daily vapor pressure deficit during the growing season ($\overline{\text{VPD}}$). The study provides evidence for the need to moderately increase pearl millet plant population and fertilizer application in the Sahel to efficiently use available water without risk of crop failure through depletion of soil water reserves. It also provides a practical, albeit empirical, basis for predicting yield under different management systems from seasonal ET and $\overline{\text{VPD}}$ data.

W.A. Payne, Columbia Basin ARC, Oregon State Univ., P.O. Box 370, Pendleton, OR 97801. Contribution of the ICRISAT Sahelian Ctr., B.P. 12404, Niamey, Niger (via Paris). Received 16 Oct. 1995. *Corresponding author (paynew@ccmail.orst.edu).

Published in Agron. J. 89:481–490 (1997).

ALTHOUGH DROUGHT OCCURS OFTEN in the West African Sahel, several studies have concluded that soil nutrient availability is more limiting than water availability to pearl millet production. These conclusions were based largely on fertility-response data during wet and dry years (e.g., Bationo et al., 1989; Timofeyev et al., 1988) and soil water balance data (Cissé and Vachaud, 1988; Payne et al., 1990a; Klaij and Vachaud, 1992; van Duivenbooden and Cissé, 1993). In the water balance studies, pearl millet water-use efficiency (WUE), defined as yield/ET, was found to be very low compared with WUE of other cereal crops. Cissé and Vachaud (1988) and Klaij and Vachaud (1992) noted further that, in contrast to many crops, pearl millet yield could not be predicted from cumulative evapotranspiration (ET).

Low WUE can be addressed by at least three management options: (i) fertilizer addition, (ii) increased plant population, and (iii) use of more water-efficient genotypes. When rainfall is limiting, however, these options might increase ET to the point of exhausting plant-available water before maturity (Viets, 1962). This would increase risk of crop failure, which subsistence farmers in the Sahel must avoid. A popular view is that keeping plant populations low and maintaining fields at low fertility reduces crop water use and thereby minimizes risk of crop failure. The objectives of this study were to determine the effects of the three management options listed above on (i) pearl millet yield, ET, and other water balance terms and (ii) yield–ET relations for a range of Sahelian climatic conditions.

Abbreviations: *D*, root-zone drainage; DM, aboveground dry matter production; DOY, day of year; d*S*, change in root-zone soil water storage; ET, evapotranspiration; INERA, Institut National d'Études et de Recherches Agricoles, Burkina Faso; INRAN, Institut National de Recherches Agronomiques du Niger; $\overline{\text{VPD}}$, mean daily vapor pressure deficit for growing season; WUE, water-use efficiency.

MATERIALS AND METHODS

Three experiments were conducted between 1983 and 1990 at the ICRISAT Sahelian Center (13°15′ N; 2°17′ E), near Niamey, Niger, where mean annual rainfall is 580 mm. Surface soil horizons at the Sahelian Center have a sandy loam to loamy sand texture, a pH in water (1:1) of ≈5.5, a CEC of ≈0.9 cmol kg^{-1}, and an organic matter content of ≈3 g kg^{-1}. In the U.S. system of soil taxonomy, the soils are classified as sandy, silicious, isohypothermic Psammentic Kandiustalfs.

Experiments

The experiments were (i) a Nitrogen × Plant population experiment, conducted in 1983, which used one genotype, three N levels, and three plant spacings; (ii) a Fertility × Plant population × Genotype experiment conducted in 1984 and 1985, which included three fertility levels, three genotypes, and three plant spacings; and (iii) a Genotype × Fertility experiment, conducted in 1990, which used five genotypes at three fertility levels. In all experiments, plants were thinned to three plants per hill ≈15 d after sowing. Pertinent genotype information is given in Table 1.

Agronomic aspects of the N × Plant population experiment, which was carried out in 1983, 1984, and 1985, were reported by Bationo et al. (1990). Water-use data, which were not reported by Bationo et al. (1990), were collected only in 1983. The experiment consisted of a split-plot factorial design arranged in four randomized complete blocks, with plant population as the main plot treatment and N rate as the subplot treatment. Main plots were 21 by 11 m, and consisted of four 5- by 10-m subplots separated by alleys 1 m wide. Phosphorus was applied as single superphosphate at 13.6 kg P ha^{-1}, and K as KCl at a rate of 25 kg K ha^{-1}. Seeds were planted without ridging in rows 1 m apart. Water-use data were collected for plant populations of 5000, 10 000, and 20 000 hills ha^{-1}, and for N rates of 0, 20, and 40 kg N ha^{-1}. Nitrogen was split-applied as urea. The first split was broadcast 3 wk after sowing, and the second was broadcast and incorporated at 6 wk after sowing. The variety used was CIVT (Table 1).

In 1984 and 1985, experimental factors were fertility, plant population and genotype. A fourth factor, not relevant to this paper, was cowpea [*Vigna unguiculata* (L.) Walp.] intercrop. Fertilizer levels were (i) 0 kg N ha^{-1} and 0 kg P ha^{-1}, (ii) 23 kg N ha^{-1} and 8.8 kg P ha^{-1}, and (iii) 46 kg N ha^{-1} and 17.6 kg P ha^{-1}. Phosphorus was broadcast-applied before planting as single superphosphate. Nitrogen was applied as calcium ammonium nitrate in two side dressings at approximately 2 wk and 1 mo after sowing. Pearl millet was sown on ridges at plant populations of 5000, 10 000, and 20 000 hills ha^{-1}. Varieties used were CIVT, Sadoré Locale, and the hybrid ICH 412 (Table 1). The experimental design was a split plot with six blocks for the first two varieties, but only three for ICH 412 in 1984 because it was not used in the intercropped treatment. There were three blocks for all varieties in 1985. Subplot dimensions were 6 by 6 m.

The 1990 experiment also used a split-plot design, with fertility level as the main plots and genotypes as subplots in six blocks. However, only three main plots of each fertility level were installed with access tubes, such that soil water content was measured in three plots of each variety at each fertility level. Subplots were 18 by 3 m, and consisted of four ridges spaced at 0.75 m apart. Hills were planted 0.60 m apart on ridges, giving a plant population of 22 220 hills ha^{-1}. Fertility treatments were identical to those of the 1983 experiment. Varieties were IKMV 8201, ICMV IS 85321, ICMV IS 85327, P3 Kolo, and Sadoré Locale (Table 1).

For purposes of discussion, fertility levels and plant populations in each experiment were classified as low, medium, and high. However, the low-fertility treatment in the 1983 N × Plant population experiment had a basal application of P for the low-fertility treatment, whereas in the other experiments the low-fertility treatment had no P application. The 1990 Fertility × Genotype experiment used only a high plant population.

Water Balance and Water-Use Efficiency

For each experiment, soil water content was determined weekly, using gravimetric sampling for the upper 0.25 m of the soil profile and a Troxler (Research Triangle Park, NC) Model 3322 neutron probe at greater depths. Access tubes were installed to a depth of 2.6 m. Evapotranspiration was calculated from the water balance equation

$$dS = R - (ET + D) \qquad [1]$$

where dS is the change in soil water storage in the root zone, R is rainfall, ET is evapotranspiration, and D is root-zone drainage. Equation [1] assumes that runoff, runon, lateral flow, and upward capillary flow are negligible. These assumptions were based on infiltration data of Hoogmoed et al. (1991) and hydraulic gradient data of Payne et al. (1990b). Experimental fields had slopes of less than 2%.

The root zone was assumed to be 1.5 m deep, based on published (Payne et al., 1996, 1990a) and unpublished studies at the Sahelian Center and surrounding sites. The term D was calculated for each access tube using the two-stage method of Klaij and Vachaud (1992). To calculate D during the second stage (i.e., after the wetting front has passed the bottom of the access tube), we used the hydraulic conductivity function of Hartman and Gandah (1982), which was determined at a nearby site with similar soil characteristics. Neutron probe measurements were made approximately weekly.

Water-use efficiency was calculated as grain or above-ground dry matter (DM) divided by ET. In an attempt to

Table 1. Brief characterization of the pearl millet genotypes used in the three experiments.

Genotype	Description	Days to maturity	Source†	Year‡
ICH 412	Hybrid, IIA × ICP 412	90	ICRISAT	1984, 1985
IKMV 8201	Derived from germplasm accession P449 from Mali	90	INERA/ICRISAT	1990
ICMV/IS 85327	Derived from crosses between local cultivars	90	ICRISAT	1990
ICMV/IS 85321	Derived from INRAN-ICRISAT genepool INMG 1-1	90	ICRISAT	1990
Sadoré Locale	Local source of Heini Kiri, the predominant landrace of western Niger	110	Sadoré Village	1984, 1985, 1990
CIVT	Derived from recombining lines from local cultivars Kolo, HKN, Guerguera, and Tampagagi	95	INRAN	1983, 1984, 1985
P3 Kolo	Derived from four local cultivars	90–95	INRAN	1990

† INERA, Institut National d'Études et de Recherches Agricoles, Burkina Faso; INRAN, Institut National de Recherche Agronomique du Niger.
‡ 1983: Nitrogen × Plant population experiment. 1984, 1985: Fertility × Plant population × Genotype experiment. 1990: Genotype × Fertility experiment.

correct for year-to-year differences in atmospheric evaporative demand, WUE was divided by the average daily atmospheric water vapor pressure deficit during the growing season ($\overline{VPD}$) (De Wit, 1958), and by the sum of average daily vapor pressure deficit between neutron probe measurements, summed over all measurement intervals during the season (ΣVPD_{probe}). The latter was used to approximate the daily integral of vapor pressure deficit (Tanner and Sinclair, 1983). Daily mean vapor pressure deficit was calculated as the mean of vapor pressure deficit determined at 0700 and 1300 h. Air temperature and relative humidity, measured at 2 m height within 150 m of experimental plots, were used to calculate vapor pressure deficit using the equations of Campbell (1977). Analyses of variance for yield, ET, and WUE data were made using GENSTAT (Numerical Algorithms Group, Ltd., Oxford, UK). Linear regression of yield–ET, yield–ET/$\overline{VPD}$, and yield–ET/ΣVPD_{probe} relations were made using SYSTAT (SPSS, Chicago, IL).

RESULTS AND DISCUSSION

Weather

The four growing seasons contrasted one another considerably (Fig. 1). Both 1983 (602 mm total rainfall) and 1985 (545 mm total rainfall) could be considered as good years, but the 1983 season started much earlier than the 1985 season, and therefore was much longer. The 1990 season (400 mm total rainfall) was dry, but not severely so. The 1984 season (260 mm total rainfall) was the driest on record for this region, and caused widespread food shortages. Average daily vapor pressure deficit between neutron probe measurements also differed (Fig. 1). Mean daily vapor pressure deficit for the entire growing season was 0.80 kPa in 1983, 1.70 kPa in 1984, 1.28 kPa in 1985, and 1.46 kPa in 1990.

Yield Response

Analysis of variance for the 1983 data showed no interaction between N and plant population treatments on yield in 1983. Grain and DM yield increased greatly from low to high fertility levels and low to medium plant populations (Table 2). There was no further yield increase from medium to high fertility levels, and there was an apparent reduction in yield at plant populations of 10 000 and 20 000 hills ha^{-1}. Bationo et al. (1990), however, reported further yield increases using greater plant populations (40 000 hills ha^{-1}) and at greater N rates (60 kg N ha^{-1}).

Despite the fact that 1984 was the driest year on record, grain yield increased from low to high plant population, and from low to medium fertilizer application (Table 3). Dry matter yield increased from low to high fertility, but decreased from low to high plant population. There were also grain yield differences among genotypes. In every factor combination, the early hybrid ICH 412 equaled or surpassed the other varieties. This was undoubtedly due to its earliness (Table 1). The intermediate variety, CIVT, generally performed better

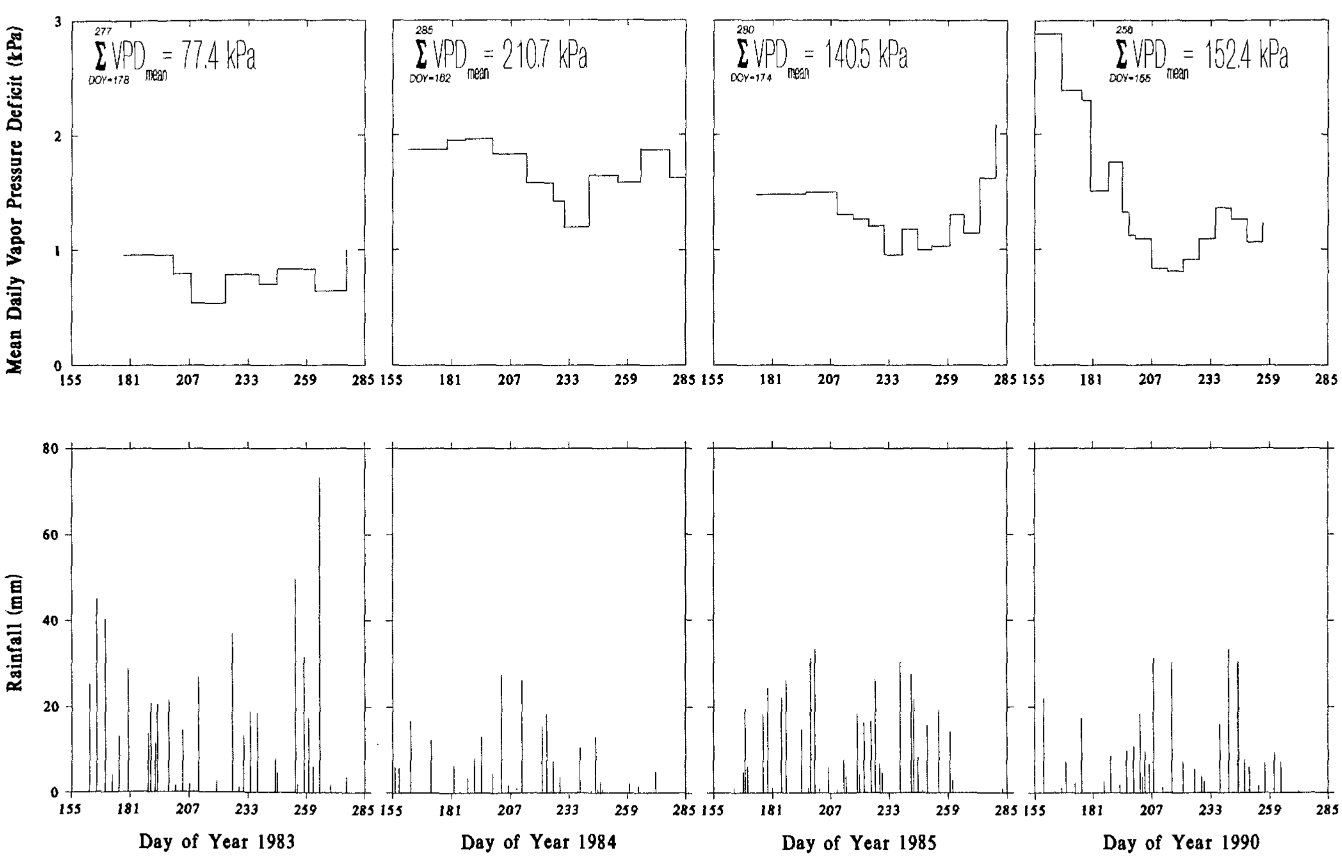

Fig. 1. Mean daily vapor pressure deficit between neutron probe measurements and rainfall patterns at Sadoré, Niger, in 1983, 1984, 1985, and 1990. The sum of mean vapor pressure deficit between probe measurements for the growing cycle of the latest-maturing variety is also indicated.

Table 2. Grain yield, aboveground dry matter (DM) yield, grain water-use efficiency (WUE), and aboveground DM WUE of pearl millet as affected by fertilizer application and plant population in 1983.†

	Yield		Water-use efficiency	
	Grain	DM	Grain	DM
	— kg ha^{-1} —		— kg ha^{-1} mm^{-1} —	
Fertility				
Low	1344	3871	4.5	12.9
Medium	1950	5307	7.2	17.8
High	1870	5305	5.9	16.6
Mean	1721	4828	5.8	15.8
SE	135	182	0.60	0.55
Plant population, hills ha^{-1}				
5 000	743	2018	2.5	6.8
10 000	2347	6849	7.8	22.7
20 000	2074	5618	7.3	17.8
Mean	1789	4828	5.8	15.8
SE	131	219	0.56	0.73

† Evapotranspiration data are not presented, due to statistical interaction between fertility and plant population treatments.

than the relatively late-maturing Sadoré Locale. When planted using more-or-less traditional practices (i.e., at plant populations ≤ 10 000 hills ha^{-1} with no fertilizer input), grain yield was less than 200 kg ha^{-1} for the local landrace, illustrating why 1984 was a year of famine in Niger. Consistent with 1983 results, there were no interactions between fertilizer application, plant population, or genotype.

Rainfall in 1985 was only slightly below the annual mean, and yield was considerably greater than in 1984 (Table 4). Grain and DM yield increased greatly from low to high fertilizer application, and from low to medium plant population. There was a decrease in grain yield from medium to high plant population, but a slight increase in DM yield. There were also main effects due to genotype. The local landrace had the least grain yield but the greatest DM yield, whereas the reverse was true for the hybrid ICH 412. As with the 1983 and 1984 data, there was no interaction between experimental factors on yield.

Table 3. Grain yield, aboveground dry matter (DM) yield, evapotranspiration (ET), grain water-use efficiency (WUE), and aboveground dry matter water-use efficiency (DM WUE) of pearl millet as affected by fertilizer application, plant population, and genotype in 1984.

	Yield			WUE	
	Grain	DM	ET	Grain	DM
	— kg ha^{-1} —		mm	- kg ha^{-1} mm^{-1} -	
Fertility					
Low	257	1350	219	1.17	6.1
Medium	383	2008	226	1.71	8.9
High	351	2096	225	1.57	9.3
Mean	330	1815	223	1.48	8.1
SE	46	110	1.7	0.20	0.43
Plant population, hills ha^{-1}					
5 000	297	1971	226	1.31	8.7
10 000	324	1784	222	1.46	8.0
20 000	370	1689	222	1.67	7.6
Mean	330	1815	223	1.48	8.1
SE	16.6	65	1.2	0.07	0.30
Genotype					
Sadoré Locale	222	1749	230	0.96	7.6
CIVT	370	1754	221	1.65	7.9
ICH 412†	468	2067	213	2.19	9.7
Mean	330	1815	223	1.48	8.1
SE	15	60	1.1	0.07	0.27

† For ICH 412, the SE should be multiplied by 1.4, because it was used in only half the replicates.

Table 4. Grain yield, aboveground dry matter (DM) yield, evapotranspiration (ET), grain water-use efficiency (WUE), and aboveground dry matter water-use efficiency (DM WUE) of pearl millet as affected by fertilizer application, plant population, and genotype in 1985.

	Yield			WUE	
	Grain	DM	ET	Grain	DM
	— kg ha^{-1} —		mm	- kg ha^{-1} mm^{-1} -	
Fertility					
Low	513	2526	359	1.45	7.1
Medium	1292	5645	368	3.54	15.3
High	1696	7703	371	4.60	21.0
Mean	1167	5291	366	3.20	14.5
SE	72	102	3.3	0.17	0.25
Plant population, hills ha^{-1}					
5 000	1052	4433	370	2.88	12.0
10 000	1300	5564	374	3.54	14.9
20 000	1150	5877	355	3.22	16.5
Genotype					
Local	1074	5915	391	2.75	15.2
CIVT	1203	5039	359	3.33	14.0
ICH 412	1224	4920	348	3.52	14.3
Mean†	1167	5291	366	3.19	14.5
SE	46	214	8.1	0.13	0.55

† Mean and SE for comparison with levels of plant populations and genotypes.

Fertilizer application greatly increased grain and DM yield in the 1990 experiment too (Table 5). Grain yield was greatest for the variety P3 Kolo, and least for IKMV 8201. Despite the fact that 1990 rainfall was low, grain and DM yields were generally similar to those of 1985. Once again, there was no interaction between genotype and fertility application on yield.

Soil Water Balance

Analysis of variance for the 1983 experiment indicated an interaction between N and plant population treatments on ET. During the growing season, ET was remarkably similar for all treatment combinations save

Table 5. Grain yield, aboveground dry matter (DM) yield, evapotranspiration (ET), grain water-use efficiency (WUE), and aboveground DM WUE of pearl millet as affected by fertilizer application and genotype in 1990.

	Yield			WUE	
	Grain	DM	ET	Grain	DM
	— kg ha^{-1} —		mm	- kg ha^{-1} mm^{-1} -	
Fertility					
Low	373	2139	270	1.40	7.9
Medium	784	5407	271	2.95	19.9
High	1055	5628	292	3.60	19.0
Mean	737	4391	278	2.65	15.6
SE	122	379	7.1	0.47	1.5
Genotype					
ICMVIS 85321	736	3497	269	2.76	13.0
ICMVIS 85327	697	4327	278	2.52	15.6
IKMV 8201	557	2993	268	2.12	11.3
P3-KOLO	1004	4511	273	3.62	16.4
Sadoré Locale	693	6629	300	2.24	21.7
Mean	737	4391	278	2.65	15.6
SE	67	344	5.0	0.21	1.1

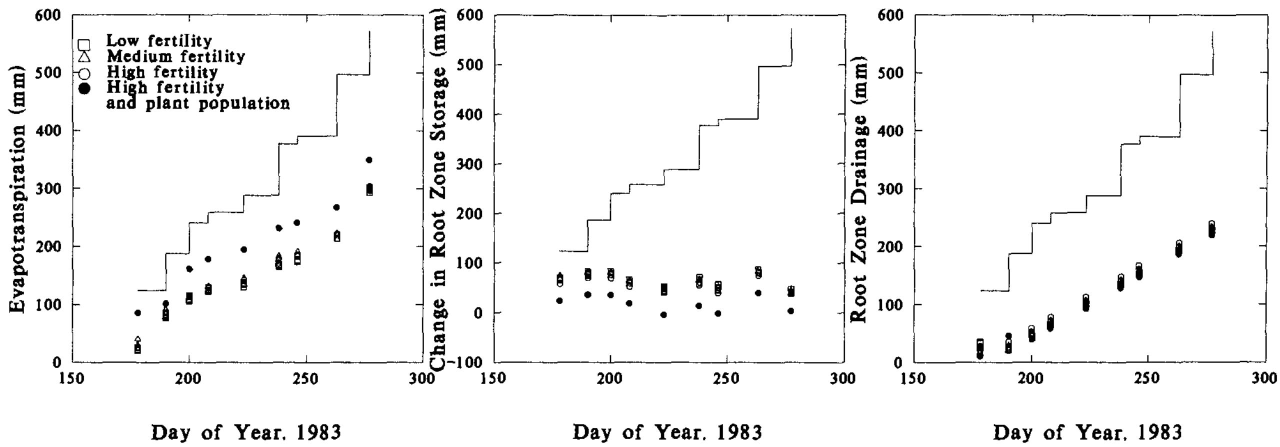

Fig. 2. Root-zone water balance as affected by fertility treatment, and by high fertility when combined with high plant population, for the 1983 N × Plant population experiment. The solid stepped line represents cumulative rainfall since the first neutron probe measurement.

the highest N and plant population combination (Fig. 2). Total ET for this combination increased by ≈50 mm relative to the other treatments, for which total ET was ≈300 mm (Fig. 2); however, ET was always less than cumulative rainfall, indicating no increased risk of exhausting soil water supply. Greater ET in the high fertility/high plant population combination resulted from lesser dS, and therefore lower water content at the bottom of the root zone. Lower water content decreased D due to lower hydraulic conductivity (Fig. 2).

The 1984 water balance data (Fig. 3) contrasted 1983 data greatly. Cumulative ET in 1984 matched cumulative rainfall closely during most of the season, then surpassed it towards the season's end, suggesting extraction of profile-stored water from 1983. Extraction of water stored from the previous year was also reported for pearl millet for an exceptionally dry year by Payne et al. (1990a). Even though rainfall was low in 1984, total ET nonetheless increased slightly due to increased soil fertility, and there were differences among genotypes (Table 4). There was no effect of plant population on ET. Although higher fertility levels slightly increased

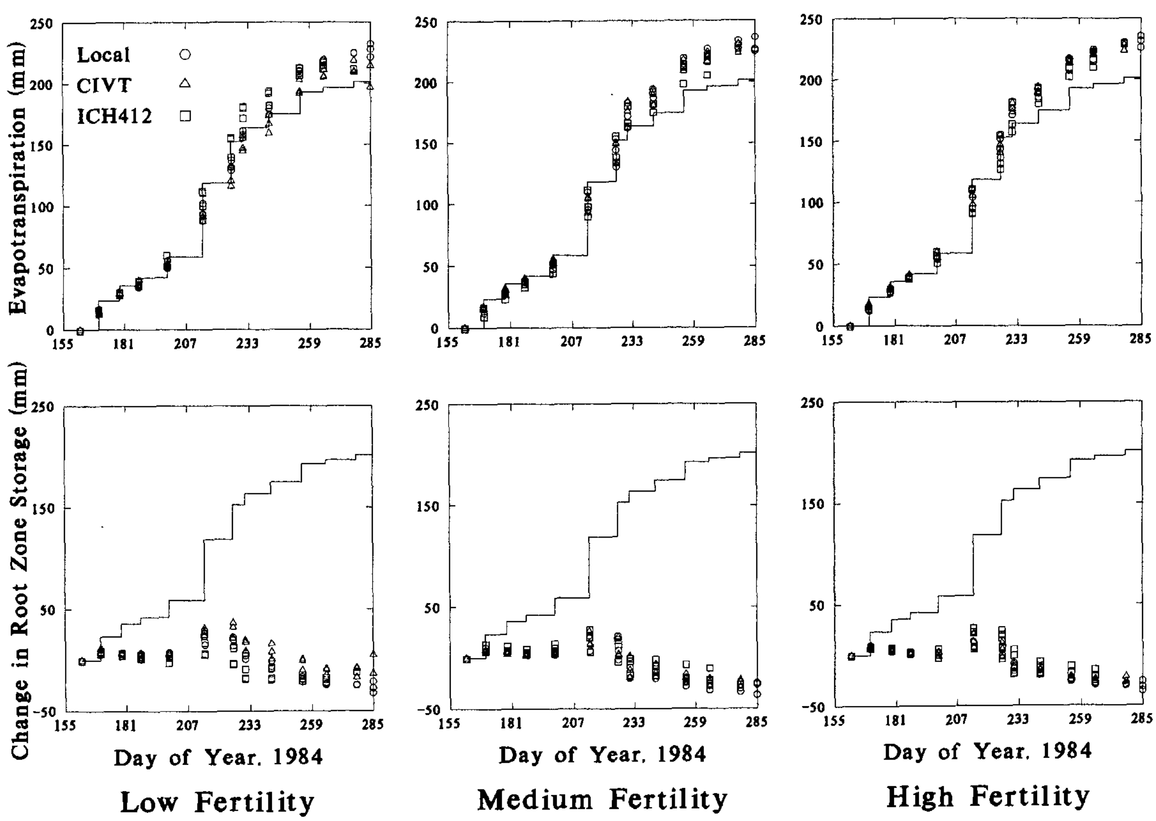

Fig. 3. Root-zone water balance as affected by fertility and genotype for all plant population treatments of the 1984 Fertility × Genotype × Plant population experiment. The solid line represents cumulative rainfall pattern during the growing season. Root-zone drainage was negligible in 1984.

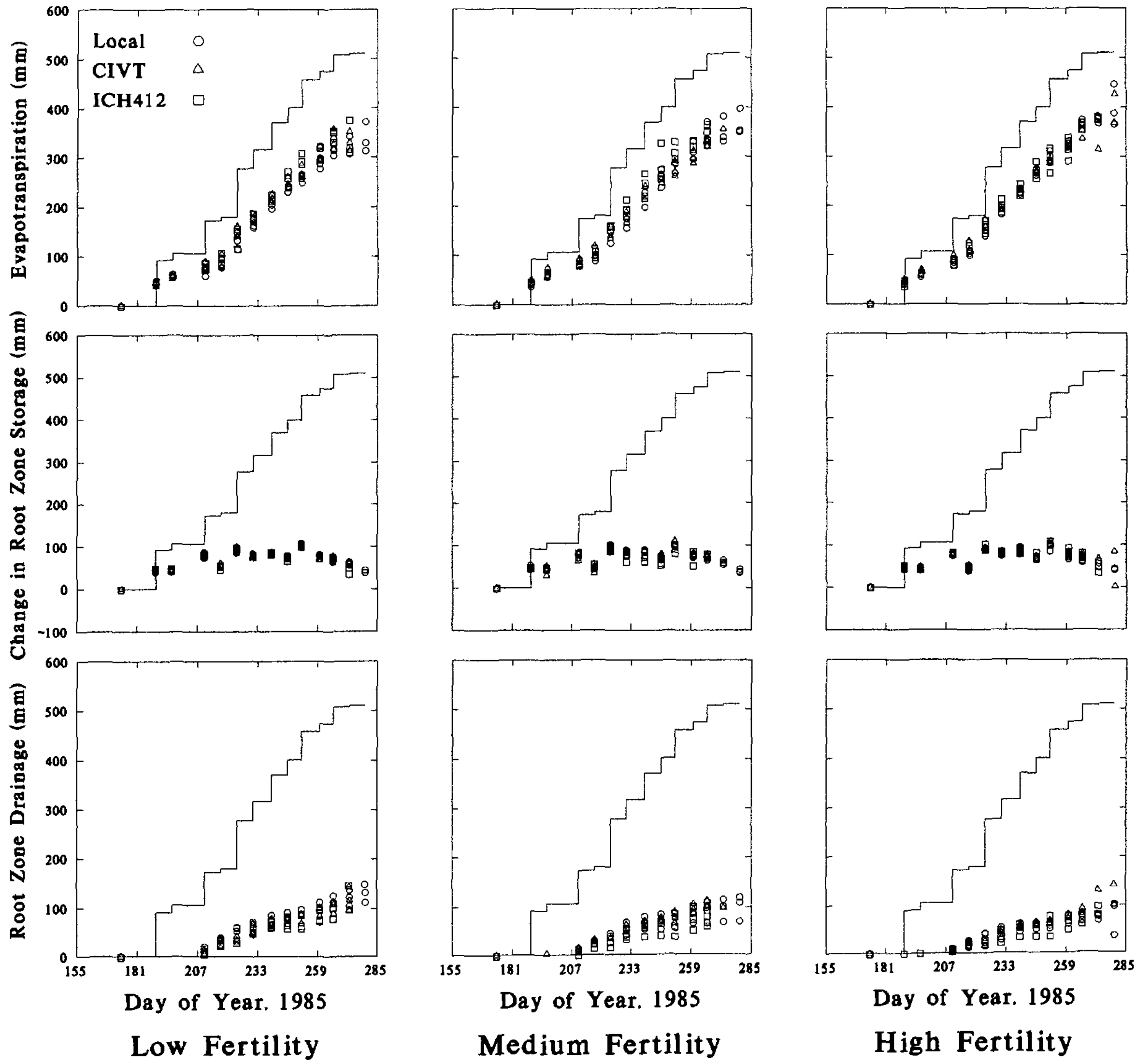

Fig. 4. Root-zone water balance as affected by fertility and genotype for all plant population treatments of the 1985 Fertility × Genotype × Plant population experiment. The solid line represents cumulative rainfall pattern during the growing season.

ET during the season, all treatments nearly exhausted plant-available water several times during the season (Fig. 3) due to catastrophically low rainfall. Therefore, it is difficult to conclude that increased fertilizer application increased the risk of exhausting crop water supply before maturity. Because of very low rainfall, *D* was negligible in 1984.

In 1985, ET increased from low to medium fertility, and decreased from medium to high plant population (Table 4). During most of the season, ET was less than rainfall, but there was a dry spell that occurred before Day of Year 224 (DOY 224), when cumulative rainfall was 180 mm (Fig. 4). Averaging across genotypes (there was no effect of genotype on ET at this time), ET was 136 mm for low-fertility plots and 164 mm for high-fertility plots. Although this might suggest some increased risk of exhausting available water supply before crop maturity due to fertilizer addition, yield and WUE further increased as fertility level went from medium to high (Table 4). This slight increase of ET due to increased soil fertility was reflected by a slightly decreased *D* relative to low-fertility treatments (Fig. 4). After 224 DOY, ET was much less than cumulative rainfall.

Unlike the 1984 season, which was catastrophically dry, the 1990 season represented the type of drought that a farmer at this latitude might see once in a decade or so. Water balance data for 1990 (Fig. 5) were therefore particularly interesting. From medium to high fertility levels in 1990, total ET increased by ≈20 mm. (Table 5). Among genotypes, Sadoré Locale had the greatest ET (300 mm), which was 20 to 30 mm greater than ET for the other genotypes. Throughout 1990, *D* was negligible. Figure 5 shows that high-fertility treatments tended to have slightly higher ET throughout the growing season. At season's end, the late-maturity local landrace had total ET greater than total rainfall, suggesting some extraction of water stored at lower soil depths from the previous year. The water balance data therefore suggest increased risk of exhausting available water

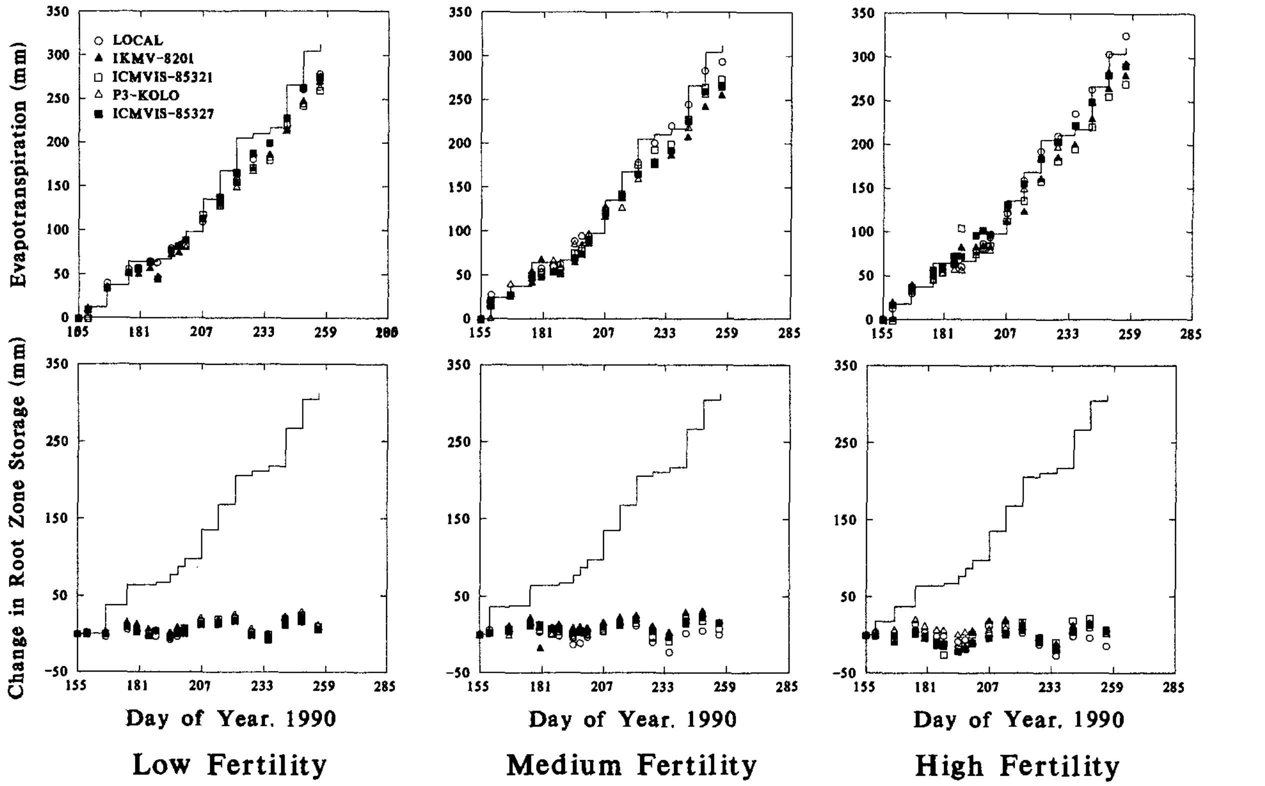

Fig. 5. Root-zone water balance as affected by fertility and genotype of the 1990 Fertility × Genotype experiment. The solid line represents cumulative rainfall pattern during the growing season. Root-zone drainage was negligible in 1990.

supply due to greater ET in the highest fertility level, especially for the local landrace. As with the 1985 data, however, the greater ET due to increased fertilizer addition was associated with substantially increased yield and WUE (Table 5).

Overall, water balance data from 1984, 1985, and 1990 suggest that any genotypic differences in ET were mostly related to length of the growing cycle (see Table 1). For example, total ET in 1984, averaged across all fertility and plant population treatments, was 230 mm for Sadoré Locale, 221 mm for CIVT, and 213 mm for ICH 412 (Table 3). Similarly, in 1985 total ET was 391 mm for Sadoré Locale, 359 mm for CIVT, and 348 mm for ICH 412.

Water balance data show that fertilizer addition slightly increased ET. Although calculations of d*S* seemed to suggest that, in dry years, high levels of fertilizer addition might increase risk of exhausting available soil water reserves before maturity, there was no evidence of yield loss during the two dry years (Tables 3 and 5).

Increased plant population had a generally positive effect on yield, but little if any effect on total ET. Indeed, the 1985 data suggest that higher plant population decreased ET. Combining high fertility levels with high plant population increased ET by ≈50 mm in the wettest year (Fig. 2), but water balance data showed there were ample soil water reserves. The yield and water balance data therefore do not support the popular view that, by maintaining fields at low fertility and low plant populations, farmers reduce risk of crop failure during drought by reducing water use. Water balance data suggest further that, during average and wet years, high fertilizer application, alone or combined with high plant populations, tended to decrease d*S* and *D*, thereby increasing the amount of water available to the crop.

Water-Use Efficiency

Even though the data sets on yield and soil water balance are not rigidly compatible in terms of experimental design over the four years, to our knowledge they offer the best opportunity thus far to draw general conclusions on how the management factors of genotype choice, fertilizer addition, and plant population can affect pearl millet water use and WUE under a range of climate conditions in the Sahel.

Mean values for yield and ET of each combination of plant population and fertility level from the four years of data are pooled in Fig. 6 for the three most commonly used varieties in these experiments (i.e., Sadoré Locale, CIVT, and ICH 412). These data illustrate why Cissé and Vachaud (1988) and Klaij and Vachaud (1992) found it difficult to predict pearl millet yield from ET. The lack of a linear relation between yield and ET contrasts sharply with that reported for grain sorghum [*Sorghum bicolor* (L.) Moench] (Stewart, 1989) and maize (*Zea mays* L.) (Hanks, 1983). The poor correlation may be due in part to the small range of values (i.e., relatively small variance from the mean value) on the *x*- and *y*-axes. Stewart's (1989) sorghum data, for example, ranged from 100 to 700 mm for ET, and from

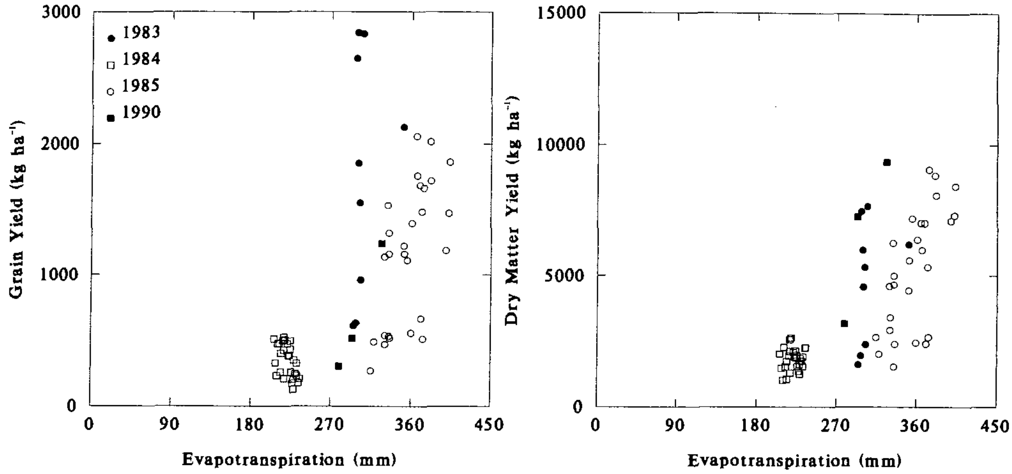

Fig. 6. Relation between pearl millet grain and dry matter yield and evapotranspiration in 1983, 1984, 1985, and 1990 at Sadoré, Niger. Points are for the varieties Sadoré Locale, CIVT, and ICH 412.

less than 500 kg to nearly 10 000 kg ha^{-1} for grain yield. Our data ranged only from ≈200 mm to ≈400 mm for ET, and from ≈200 to ≈2000 kg ha^{-1} for grain yield. However, poor correlation is probably due mostly to the relative insensitivity of ET to management for crops with leaf area indices of less than 2 (Ritchie, 1983), which is almost always the case for pearl millet in the Sahel (e.g., Azam-Ali et al., 1984; Amadou, 1994).

In Table 6 we summarize linear regression results for yield as a function of ET, ET/$\overline{VPD}$, and ET/ΣVPD_{probe} for different categories of plant population and fertility. Some aspects of these regression equations are very much debatable, such as how points should be grouped in terms of fertility and plant population, whether a linear model is the most appropriate, and whether some points ought to be excluded as outliers. For example, the very poor linear relation shown for DM and ET/ΣVPD_{probe} at low plant population and low fertility is due mostly to one point from 1983. A general conclusion, however, is that there were two or perhaps three fertility-dependent linear relations for yield and ET for the two categories of plant population (low and medium-to-high). The increase in slope with increased fertility is consistent with studies of the effects of P and N fertilization on wheat yield–ET relations (Power et al., 1961; Jensen and Sletten, 1965). The data also lend empirical support to Forest et al.'s (1991) model, which uses fertility-dependent curves of pearl millet yield as a function of ET/ETM, where ETM is atmospheric potential evaporation, to predict yield for farmers' fields in West Africa.

The practical advantage of correcting ET for seasonal vapor pressure deficit to predict DM and grain yield can be evaluated from regression models with and without vapor pressure deficit correction (Table 6). Overall, these results indicate that $\overline{VPD}$ is a useful term to incorporate into ET-based models of yield for millet, especially for grain yield, whereas using ET/ΣVPD_{probe} gave

Table 6. Results of linear regression of pearl millet grain and dry matter yield on evapotranspiration (ET) and the ratios of ET to mean daily vapor pressure deficit (ET/$\overline{VPD}$) and to mean daily vapor pressure deficit between neutron probe measurements of soil water content, summed over the growing season (ET/ΣVPD_{probe}). Pearl millet was grown in 1983, 1984, 1985 and 1990 in Niger, West Africa.

Plant population	Soil fertility	Slope			Intercept			R^2			SEE‡		
		ET	ET/$\overline{VPD}$	ET/ΣVPD†	ET	ET/$\overline{VPD}$	ET/ΣVPD	ET	ET/$\overline{VPD}$	ET/ΣVPD	ET	ET/$\overline{VPD}$	ET/ΣVPD
							Grain yield						
Low	Low	1.98	1.83	145	−165	22	99	0.63	0.68	0.79	117	109	91
	Medium	6.67	5.91	316	−1135	−417	87	0.90	0.93	0.70	162	139	255
	High	7.07	6.76	336	−1240	−552	94	0.94	0.96	0.44	165	165	469
Medium to high	Low	1.85	1.66	373.8	−119	69	−240	0.63	0.56	0.65	393	107	302
	Medium	7.01	8.27	727.8	−918	−755	−504	0.3	0.85	0.86	543	326	314
	High	9.39	7.71	698.8	−1570	−551	−294	0.68	0.89	0.88	531	290	311
All points combined		5.67	5.5	505	−783	−378	−230	0.32	0.55	0.56	588	479	470
							Dry matter yield						
Low	Low	5.76	5.08	207	158	769	1301	0.56	0.54	0.22	393	405	474
	Medium	22.14	19.46	665	−2750	−337	1916	0.9	0.91	0.26	543	511	1378
	High	27.27	25.77	1 017	−3936	−1223	1652	0.96	0.96	0.25	531	542	2218
Medium to high	Low	10.17	10.05	1 069	−690	289	610	0.63	0.63	0.78	519	545	610
	Medium	31.48	22.18	1 916	−4500	−399	1304	0.71	0.73	0.72	1315	1261	1304
	High	39.27	23.80	2 100	−6427	−128	2148	0.85	0.61	0.57	1254	2038	2148
All points combined		24.3	16.0	14 101	−3343	139	716	0.47	0.38	0.36	1820	1971	2004

† ΣVPD_{probe}, the form used in the text, is here shortened to ΣVPD, under space limitations.
‡ SEE, standard error of estimate.

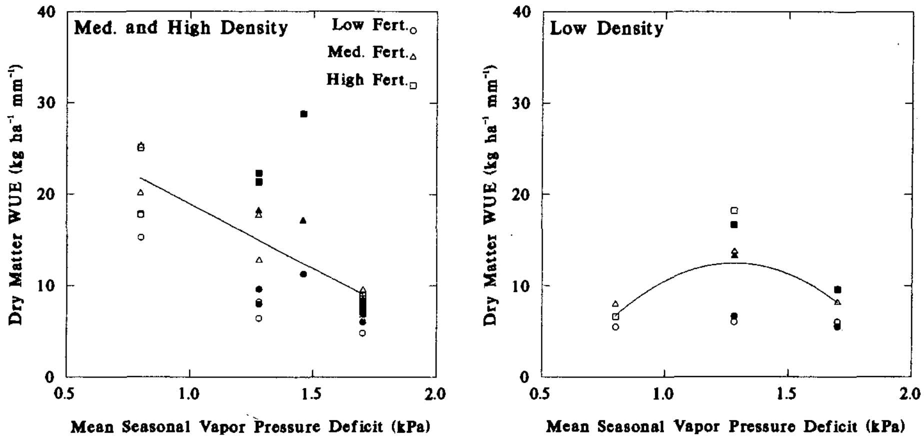

Fig. 7. Dry matter water-use efficiency (WUE) as related to mean seasonal vapor pressure deficit for three fertility levels at medium-to-high (10 000 to 22 000 hills ha^{-1}) and low (5000 hills ha^{-1}) plant population. Data are for the genotypes Sadoré Locale (open symbols) and CIVT (closed symbols).

inconsistent results. Incorporating $\overline{VPD}$ into ET-based models may be particularly useful when comparing data from sites that differ considerably in atmospheric humidity, such as landlocked Niger and coastal Senegal (Dancette, 1983).

The inverse linear relation between vapor pressure deficit and crop transpiration ratio (kg biomass kg^{-1} transpiration) predicted by theory (Tanner and Sinclair, 1983) was only partially manifested by our WUE and $\overline{VPD}$ data (Fig. 7). For all years except 1984, WUE tended to be lower for crops that were widely spaced or that received no fertilizer. Presumably this would be due to an added *clothesline* effect (Tanner, 1957, cited in Ritchie, 1983) in sparse canopies with low leaf area indices, for which vapor pressure deficit estimates from standard meteorological measurements at 2 m are probably inadequate.

Slopes in Table 6 indicate that pearl millet grain WUE, corrected for $\overline{VPD}$, is ≈1.7 kg mm^{-1} kPa^{-1} under low-fertility conditions no matter what the spacing, and varies from ≈5.9 to ≈8.3 kg mm^{-1} kPa^{-1} under high-fertility conditions. Assuming a $\overline{VPD}$ of 1.3 kPa during a normal year, and sufficient rainfall to produce a crop, this implies 1.3 kg of grain for every 1 mm of ET under low-fertility conditions, and from 4.5 kg to 6.4 kg of grain per 1 mm of ET under high-fertility conditions. These values compare well with estimates of Forest et al. (1991) of 3 kg mm^{-1} under the best of farmers' conditions and 10 kg mm^{-1} under intensive, researcher-managed conditions in Senegal. Even under high-input conditions, the grain WUE of pearl millet is considerably lower than the global value of 15.0 kg mm^{-1} for sorghum grain (Stewart, 1989).

Despite yield and WUE differences among the three plant populations, genotypes, and fertility levels, there was a strongly linear relation between WUE and yield (Fig. 8). A greater slope is shown for this relation in 1983, presumably due to the unusually low $\overline{VPD}$, and in 1984, presumably due to reduced soil evaporation caused by a more frequently dry soil surface (Ritchie, 1983). Greater WUE in 1984 may also be due in part to an increased transpiration ratio of water-stressed pearl millet (Payne et al., 1995). Data in Fig. 8 are consistent with Stewart's (1989) conclusion that greatest WUE is achieved at greatest yield. A corollary supported by this study is that managing and breeding for greater pearl millet yield also achieves greater WUE.

Overall, our data suggest that pearl millet yield and

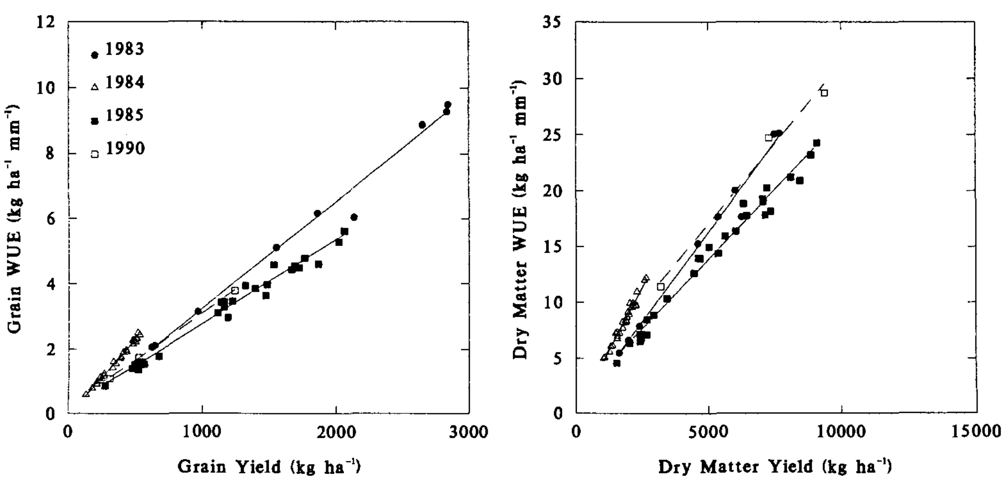

Fig. 8. Grain water-use efficiency (WUE) of pearl millet as a function of yield for 1983, 1984, 1985, and 1990 growing seasons.

WUE for most climatic zones of the Sahel can be optimized without risk of exhausting plant-available water using moderate plant populations of at least 10 000 hills ha^{-1}, and moderate fertilizer applications of ≈20 kg N ha^{-1} and ≈9 kg P ha^{-1}. Greater yields and WUE are possible using plant populations ≥ 20 000 hills ha^{-1} and fertilizer applications of ≥40 kg N ha^{-1} and ≥18 kg P ha^{-1}. Water balance data suggest that this may increase ET and therefore introduce some risk of exhausting available water during dry spells, but for our study this increased ET was associated with greater yield even during dry years.

ACKNOWLEDGMENTS

This study used unpublished data of L.K. Fussel and P.S. Soman, formerly with the ICRISAT Sahelian Center. The author thanks R.D. Stern, formerly Principal Statistician at the Sahelian Center, for help with statistical analyses and reporting, and two anonymous reviewers for valuable comments on earlier manuscript versions.

REFERENCES

Amadou, M. 1994. Analyse et modélisation de l'évaporation-transpiration d'une culture de mil en region aride Sahélienne. Thèse de Docteur en Sciences. Univ. of Paris.

Azam-Ali, S.N., P.J. Gregory, and J.L. Monteith. 1984. Effects of plant population on water use and productivity of pearl millet (*Pennisetum typhoides*) grown on stored water: I. Growth of roots and shoots. Exp. Agric. 20:203–214.

Bationo, A.B., C.B. Christianson, and W.E. Baethgen. 1990. Plant density and nitrogen fertilizer effects on pearl millet production in Niger. Agron. J. 82:290–295.

Bationo, A.B., C.B. Christianson, and U. Mokwunye. 1989. Soil fertility management of the pearl millet-producing sandy soils of Sahelian West Africa: The Niger experience. p. 159–168. *In* C. Renard et al. (ed.) Soil, crop, and water management systems for rainfed agriculture in the Sudano–Sahelian Zone. Proc. Int. Workshop, ICRISAT Sahelian Ctr., Niamey, Niger. 11–16 Jan. 1987. ICRISAT, Patancheru, AP, India.

Campbell, G.S. 1977. An introduction to environmental biophysics. Springer-Verlag, New York.

Cissé, L., and G. Vachaud. 1988. Influence d'apports de matière organique sur la culture de mil et d'arachide sur un sol sableux du Nord-Sénégal: I. Bilans de consommation, production et développement racinaire. Agronomie (Paris) 8:315–326.

Dancette, C. 1983. Besoins en eau du mil au Sénégal: Adaptation en zone semi-aride tropicale. Agron. Trop. 38(4):267–280.

De Wit, C.T. 1958. Transpiration and crop yield. Versl. Landbouwk. Onderz. 64(6).

Duivenbooden, N. van, and L. Cissé. 1993. Fertilization of millet cv. Souna III in Senegal: Dry matter production and nutrient uptake. Fert. Res. 35:217–226.

Forest, F., F. Noél-Reyniers, and B. Lidon. 1991. Prendre en compte le risque agroclimatique et le cout de l'intensification pour analyser la faisabilité de l'innovation. p. 531–541. *In* C. Pieri (ed.) Savanes d'Afrique, terres fertiles? Actes des Rencontres Internationales, Montpellier, France. 10–14 Dec. 1990. Centre de coopération internationale en recherche agronomique pour le developpement (CIRAD), Montpellier.

Hanks, R.J. 1983. Yield and water-use relationships: An overview. p. 393–412. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in production. ASA, CSSA, and SSSA, Madison, WI.

Hartmann, R., and M. Gandah. 1982. Hydrodynamic characterization of a sand dune soil in Niger. Meded. Fac. Landbouwwet. Rijksuniv. Gent 47:1195–1204.

Hoogmoed, W.B., M.C. Klaij, and J. Brouwer. 1991. Infiltration, runoff, and drainage in the Sudano–Sahelian zone. p. 85–98. *In* M.V.K. Sivakumar et al. (ed.) Soil water balance in the Sudano–Sahelian zone. Proc. Workshop, Niamey, Niger. 18–23 Feb. 1991. IAHS Publ. no. 199. IAHS Press, Inst. of Hydrology, Wallingford, UK.

Jensen, M.E., and W.H. Sletten. 1965. Evapotranspiration and soil moisture–fertilizer inter-relations with irrigated winter wheat in the southern High Plains. USDA/TAES Conserv. Rep. no. 4.

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

Payne, W.A., H. Brück, B. Sattelmacher, S.V.R. Shetty, S.V.R., and C. Renard. 1996. Root growth and soil water extraction of three pearl-millet varieties at three phenological stages. p. 251–259. *In* Dynamics of roots and nitrogen in cropping systems of the semi-arid tropics. Proc. Int. Workshop, Patancheru, India. 21–25 Nov. 1994. ICRISAT Asia Ctr., Patancheru, AP.

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

Payne, W.A., C.W. Wendt, and R.J. Lascano. 1990a. Root zone water balances of three low-input millet fields in Niger, West Africa. Agron. J. 82:813–819.

Payne, W.A., C.W. Wendt, and R.J. Lascano. 1990b. Bare fallowing on sandy fields of Niger. Soil Sci. Soc. Am. J. 54:1079–1084.

Power, J.F., D.L. Grunes, and G.A. Reichmann. 1961. The influence of phosphorus fertilization and moisture on growth and nutrient absorption by spring wheat: I. Plant growth, N uptake, and moisture use. Soil Sci. Soc. Am. Proc. 25:207–210.

Ritchie, J.T. 1983. Efficient water use in crop production: Discussion on the generality of relations between biomass production and evapotranspiration. p. 29–44. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in production. ASA, CSSA, and SSSA, Madison, WI.

Stewart, B.A. 1989. Conjunctive use of rainfall and irrigation in semi-arid regions. p. 107–116. *In* C. Renard et al. (ed.) Soil, crop, and water management systems for rainfed agriculture in the Sudano–Sahelian Zone. Proc. Int. workshop, ICRISAT Sahelian Ctr., Niamey, Niger. 11–16 Jan. 1987. ICRISAT, Patancheru, AP, India.

Tanner, C.B. 1957. Factors affecting evaporation from plants and soils. J. Soil Water Conserv. 12:221–227.

Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? p. 1–27. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in production. ASA, CSSA, and SSSA, Madison, WI.

Timofeyev, V.V., A.D. Dembele, and A. Danioko. 1988. Fertility of ferralitic concretionary degraded African savanna soils (Mali). Sov. Soil Sci. 20:23–28.

Viets, F.G. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223–264.