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Measurements of soil, plant and total evaporation from millet in Niger

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ABSTRACT

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In sparse dryland crops such as millet in West Africa a knowledge of total evaporation and its soil and plant components is important for the prediction of growth and yield, yet currently such data are very scarce. This paper presents measurements of soil, plant and total evaporation from millet crops grown during 1985, 1986 and 1987 at the ICRISAT Sahelian Center, Sadoré, Niger. Total evaporation was measured using an eddy correlation technique, transpiration using a porometer, and soil evaporation using micro-lysimeters. Soil evaporation was found to be a very important component of the crop water use, indicating that it requires explicit recognition in models of evaporation from millet. Transpiration appears to be more controlled by leaf area than stomatal conductance, which may make its prediction comparatively simple. Total evaporation, as measured by Hydra, generally agreed well with the sum of the independently measured soil and plant evaporation. However, there remains a discrepancy at high leaf area which is thought to be due to over-estimation of transpiration as a result of poor leaf area sampling in a very heterogeneous canopy. Data on total evaporation for three seasons 1985, 1986 and 1987 indicate that accurate prediction of evaporation from rainfed millet may not be achievable using the conventional crop coefficient approach. However, there is potential for developing a simple model which recognises soil and plant evaporation separately for a better prediction of both evaporation and crop yield.

INTRODUCTION

One of the principal limitations to crop growth in arid regions is the scarce and variable rainfall. However, crop performance is determined not only by the total rainfall, but also its distribution during the season, so the results of a given set of agronomic trials are often specific to the weather conditions under which they were conducted. In order to predict crop performance in the many possible weather conditions it is therefore necessary to understand the underlying processes such as evaporation that determine rainfall utilization by the crop. Furthermore, since only transpiration is directly associated with dry

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matter production, it is important to know how the total water use of a sparse crop is partitioned into transpiration and evaporation from the soil.

Despite their importance, measurements of the soil and plant components of evaporation are rarely available, especially in sparse dryland crops. Cooper et al. (1983) estimated the soil and plant components of evaporation from barley grown in Northern Syria and found that up to 60% of the seasonal rainfall evaporated directly from the soil. Data on the water use of millet grown in West Africa have been reported by Agnew (1982), who calculated total evaporation from soil moisture data. His results demonstrate the difficulty in predicting millet evaporation when the contribution from the plants and soil are not explicitly recognised (Agnew, 1991; Wallace, 1991). Azam-Ali (1983) also reported measurements of the transpiration of millet, but the crop was grown under irrigation in the dry season. These data are difficult to relate to the water use of normal rainfed millet where soil evaporation plays a much more important role. This has been demonstrated recently by Wallace (1991) who reported that between 30 and 50% of seasonal rainfall was evaporated directly from the soil in millet.

This paper reports direct measurements of soil and plant evaporation in dryland millet grown in the hot, semi-arid environment of south-west Niger. Independent measurements of total evaporation made using the eddy correlation technique are also reported and compared with the sum of the soil and plant components. The relative importance of the soil and plant components is demonstrated under a range of conditions experienced during three rainy seasons.

MATERIALS AND METHODS

Site, crop and seasons

The site was at Sadoré (13°15′N; 2°17′E), on the experimental farm of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center, located 45 km south of Niamey, Niger. The experimental field was 200 m × 200 m with the north–south boundaries lined with a windbreak of Neem trees (*Azadirachta indica* A. Juss) 4–5 m tall. A plan of the field and its fetch are given in Fig. 1. The crop studied was millet (*Pennisetum glaucum* (L.) R. Br. cv. CIVT) which was planted in rows 0.75 m apart and thinned to three plants per pocket with spacing of about 1.3 m between pockets to give a density of 30 000 plants ha^{-1}. The soil was Daybou sand about 2–3 m deep overlying laterite gravel (see West et al., 1984).

The climate of the site is typical of the southern edge of the Sahelian zone with summer rainfall and high temperatures throughout the year. Annual Penman (1948) potential evaporation at Niamey is nearly four times the mean annual rainfall of 562 mm (Sivakumar, 1987). Table 1 summarises the weather

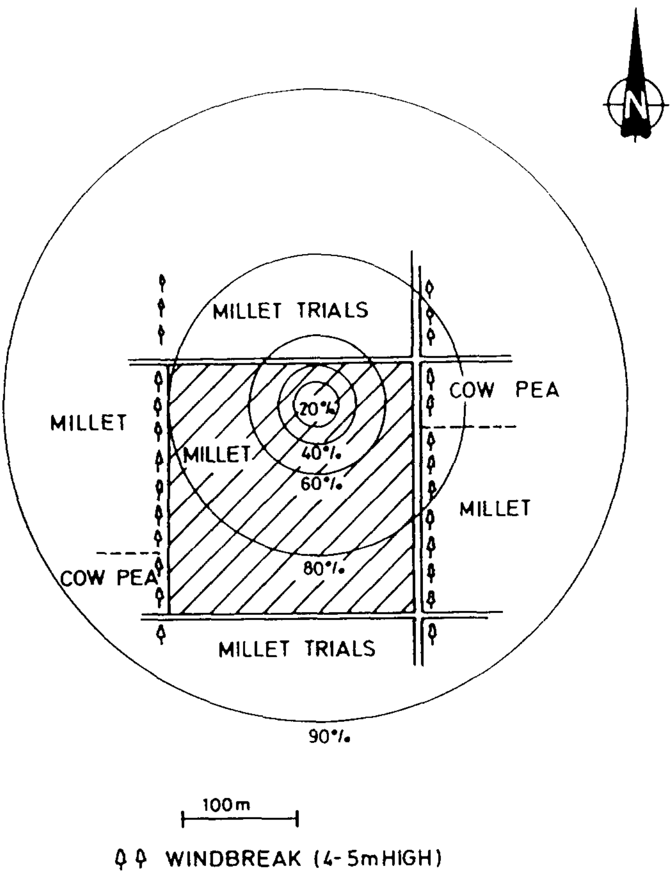

Fig. 1. Isopleths of estimated percentage effective fetch for the Hydra.

conditions during the 3 years of the study. Rainfall during the 1985 experimental period, September to October, and the entire crop season, was only slightly below average. In 1986 the rains started early in May and were about 15% above average, whereas in 1987 the rains were delayed until July and 20% below average.

Soil evaporation

The evaporation from the soil between the millet plants was measured using six small soil lysimeters. To sample any spatial variation in soil evaporation these were arranged as two sets of three in a straight line between adjacent pockets in adjacent rows, i.e. at distances of 0.25, 0.75 and 1.25 m from the millet plants . The lysimeters were made by pushing a plastic tube (15 cm diameter × 30 cm deep) into the soil between the crop rows. The soil around the tube was removed, the soil monolith extracted and a perforated base

TABLE 1

A summary of the mean weather at Niamey (Sivakumar, 1987) and the rainfall at Sadoré during 1985, 1986 and 1987

	Rainfall (mm)				Mean[b] Potential Evaporation (mm)	Mean[c] Temperature (°C)	
	Mean[a]	1985	1986	1987		Max	Min
January	0	0	0	0	161	33	16
February	0	0	0	0	167	36	18
March	2	2	1	19	207	39	23
April	7	0	1	0	209	41	26
May	34	0	84	2	219	40	27
June	77	75	61	15	203	37	25
July	142	136	177	82	156	34	24
August	194	249	189	225	131	32	23
September	88	82	119	56	137	34	23
October	16	1	25	48	171	37	24
November	1	0	0	0	158	36	19
December	0	0	0	0	143	33	16
Annual total	562	545	657	447	2057		

[a] 1905 to 1986.
[b] 1953 to 1962.
[c] 1951 to 1985.

attached to the bottom of the lysimeter. To complete the installation, the lysimeters were lowered into six lined holes located between the crop rows in another part of the field. The lysimeters were weighed on a balance with a resolution of 1 g, equivalent to 0.06 mm of water. The mean soil evaporation was calculated from the average weight loss of all six lysimeters. The lysimeters were weighed hourly from dawn to dusk on 3 days in 1985, 7 days in 1986 and a further 5 days in 1987. It is important to note that during 1986 and 1987 the lysimeters were used for only 1 day at a time with fresh soil samples being taken for each subsequent day. Using this procedure the water content of the lysimeters was kept representative of that in the surrounding field.

Transpiration

The transpiration component of the total crop evaporation was calculated from measurements of stomatal conductance and leaf area index. Stomatal conductances of the leaves were measured with an automatic diffusion porometer (AP3, Delta-T Devices, Cambridge, UK) on the same 15 days as the soil evaporation measurements were made and on 1 additional day in 1986. On each day measurements were made at 2-h intervals between dawn and dusk. Further details of the sampling procedure used are given by Wallace et al. (1990). Green leaf area index was determined from destructive samples taken from the field at approximately weekly intervals. The projected leaf area of the leaves was measured using a leaf area meter (LI-3100, LI-COR, Lincoln, NE). Stomatal conductances and leaf area index were combined to calculate the canopy conductance, allowance being made for the contribution of the panicles when present (Wallace et al., 1990).

Transpiration was calculated using the above canopy conductances in the Shuttleworth–Wallace equation (Shuttleworth and Wallace, 1985) with the appropriate hourly weather data recorded using an automatic weather station (Strangeways, 1972). Details of the method used follow that given by Wallace et al. (1990), except that the aerodynamic conductances are calculated using the scheme specified by Shuttleworth and Gurney (1990). Further details and discussion of the relative merits of different sparse crop models are given by Dolman and Wallace (1991).

Total evaporation

Total actual evaporation from the entire crop was measured using a Mk 2 Hydra eddy-correlation device (see Shuttleworth et al., 1988). This was mounted on a mast at a height of 4.5 m above the ground and approximately 50 m from the northern edge of the field (Fig. 1). The adequacy of the fetch on this site was assessed using Gash's (1986) formula. Isopleths of the estimated percentage effective fetch when the crop was present are shown in Fig. 1, indicating that for the prevailing southerly wind directions over 80% of the measured flux came from within the experimental field. Since the surrounding fields were also planted with millet trials their contribution to the flux measured by the Hydra would cause very little ($<5\%$) error. Before sowing and after the crop harvest the fetch is poorer and there was greater potential for contamination from the Neem windbreak and the surrounding fields. (Shuttleworth et al., 1988, Wallace et al., 1989). However, tests of the Hydra at this location have been reported by Shuttleworth et al. (1988) who found that it gave reliable results with an accuracy better than $\pm 10\%$.

For comparison with measurements of actual evaporation, potential evaporation was calculated using automatic weather station data in the Penman (1948) formula, with measured rather than calculated net radiation.

RESULTS AND DISCUSSION

Soil evaporation

Figure 2 shows the diurnal pattern of soil evaporation on 3 different days. The highest evaporation rates, of up to 0.4 mm h^{-1}, were obtained on 19

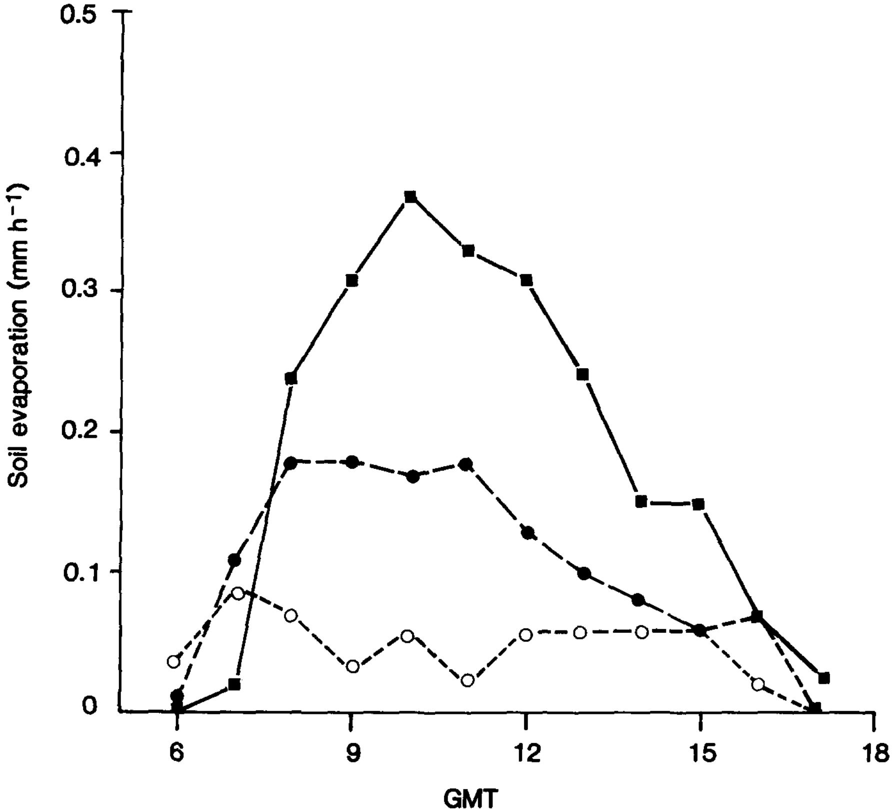

Fig. 2. The diurnal variation in soil evaporation rate on 3 days (19 September 1985 (■), 27 August 1986 (●) and 13 August 1986 (○)) with different soil wetness and leaf area index (see Table 2).

September 1985 when the soil had been recently wetted by rain (16 h before) and the leaf area index was low (0.32). On the second day shown, 27 August 1986, it had been 26 h since the last rain storm and the leaf area index was slightly higher (0.42). On this day direct soil evaporation rates were noticeably lower, only reaching approximately 0.2 mm h^{-1} in the mid-morning. When the soil surface was dry, as on 13 August 1986 when there had been no rain for 6 days, evaporation rates were very low, less than 0.1 mm h^{-1}, with little variation during the day. Low soil evaporation rates occurred when the soil surface was dry irrespective of the degree of canopy cover. Figure 3 shows the daily total soil evaporation for 15 days in 1985, 1986 and 1987. Evaporation varied from 2.4 mm day^{-1} on days shortly after re-wetting of the soil surface by rain, to as low as 0.2 mm day^{-1} in very dry soil. Soil evaporation was not measured after every rainfall event, the frequency of which (Fig. 3) indicates that substantial amounts of water would have been lost as direct soil evaporation throughout the three periods shown in 1985, 1986 and 1987.

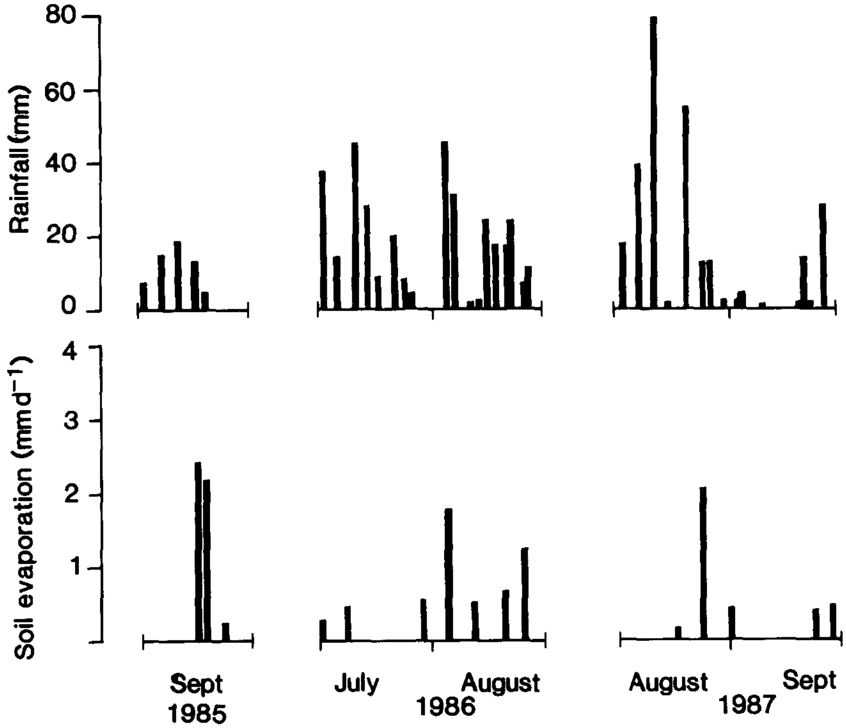

Fig. 3. Seasonal changes in daily total soil evaporation and rainfall during 1985, 1986 and 1987. Note that soil evaporation was not measured after every rain event.

The relationship between soil evaporation rate and time since the last rainfall (<2 mm) is shown in Fig. 4. This illustrates that soil evaporation rates fall off very rapidly following re-wetting of the soil surface by rain. After 3 days daily evaporation rates from the soil are less than approximately 0.5 mm day^{-1}.

Transpiration

Figure 5 shows the diurnal changes in transpiration on 3 days with different leaf area indices, but similar moist soil conditions. Transpiration rates were highly correlated with leaf area: for example, some of the highest rates were observed on 6 August 1986 when LAI was 1.5, and the lowest rates on 17 September 1985 when LAI was 0.32. Transpiration rates also tended to reach a maximum in the mid-afternoon, unlike soil evaporation rates which peaked during the morning (see Fig. 2). It was also evident by comparing Figs. 2 and 5 that the fluxes of water vapour from the soil and plants can be of equal importance, depending on the soil wetness and leaf area index.

Figure 6 shows the daily total transpiration on 16 days during 1985, 1986

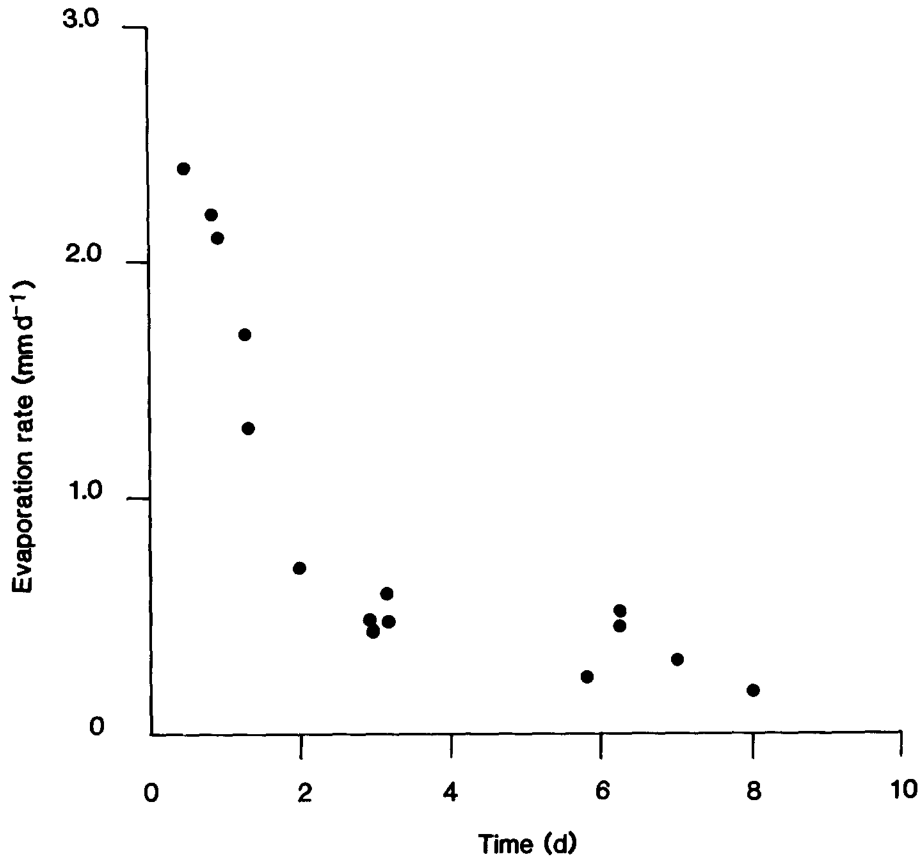

Fig. 4. Daily total soil evaporation as a function of time since the last rain storm (< 2 mm).

and 1987. Transpiration ranges from around 0.5 mm day^{-1} when the LAI was low, to around 4 mm day^{-1} at the maximum observed LAI's of between 1.5 and 2. Figure 6 also shows the midday (09:00–15:00 h) mean stomatal conductance of the uppermost leaves, g_s. Despite substantial variations in soil moisture status g_s stayed within a comparatively narrow range of 6 to 10 mm s^{-1}, implying that the observed variation in transpiration was more influenced by LAI than stomatal conductance. The strong dependence of transpiration on leaf area is further illustrated in Fig. 7 where the ratio of actual daily total transpiration (E_t), to Penman potential evaporation (E_p) is plotted as a function of leaf area index. The use of the ratio E_t/E_p rather than E_t reduces the scatter in this plot caused by changes in evaporative demand. Whether the relationship between E_t/E_p and LAI is linear or curved (at high LAI's) is dependent on the reliability of the data obtained in 1987. In either case, the

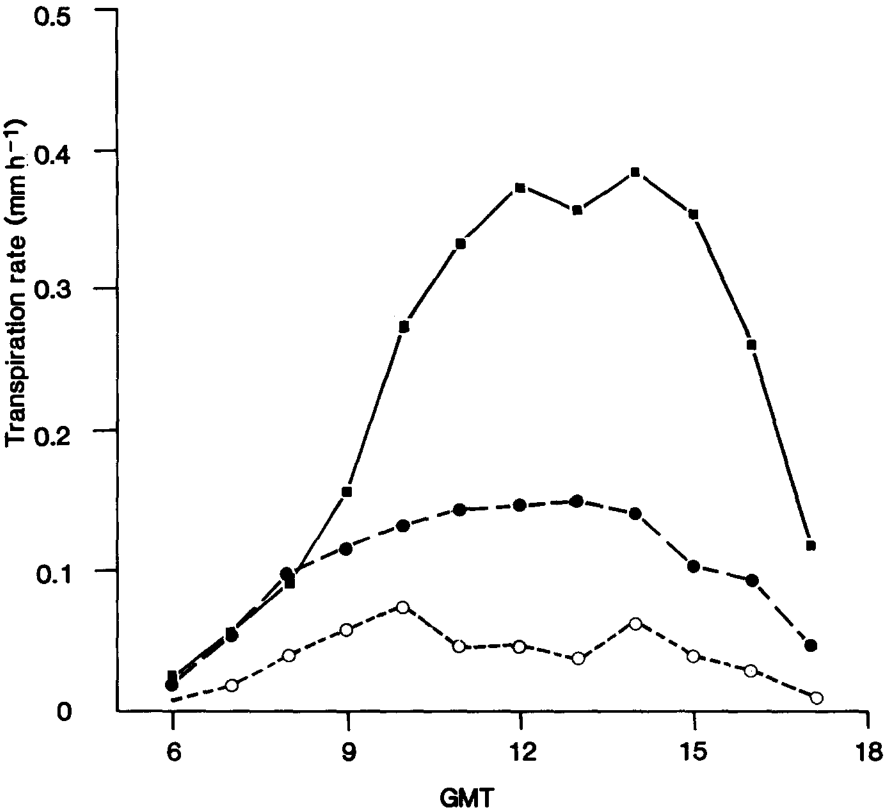

Fig. 5. The diurnal variation in transpiration on three days (17 September 1985 (○), 6 August 1986 (■) and 27 August 1986 (●)) with different leaf area indices but similar moist soil conditions (see Table 2).

implication from these data is that transpiration from millet does not reach the Penman potential rate until LAI exceeds approximately 2.

Total evaporation

Figure 8 shows a comparison of the hourly fluxes of total evaporation as measured by the Hydra (E_h) with the sum of the measured soil (E_s) and plant (E_t) evaporation under a range of conditions. When leaf area was small and transpiration low, the agreement between E_h and $E_s + E_t$ is good in both wet and dry soil, Figs. 8(a) and 8(b). When transpiration rates were higher, as in August 1986 (Figs. 8(c) and 8(d)), agreement between the two independent estimates of total evaporation is still very good under a range of soil conditions. However, there was substantial difference between E_h and $E_s + E_t$ in August/September 1987 which coincides with the occurrence of some of the highest transpiration rates recorded, Figs. 8(e) and 8(f).

Table 2 summarizes the daily soil, plant and total evaporation measured on

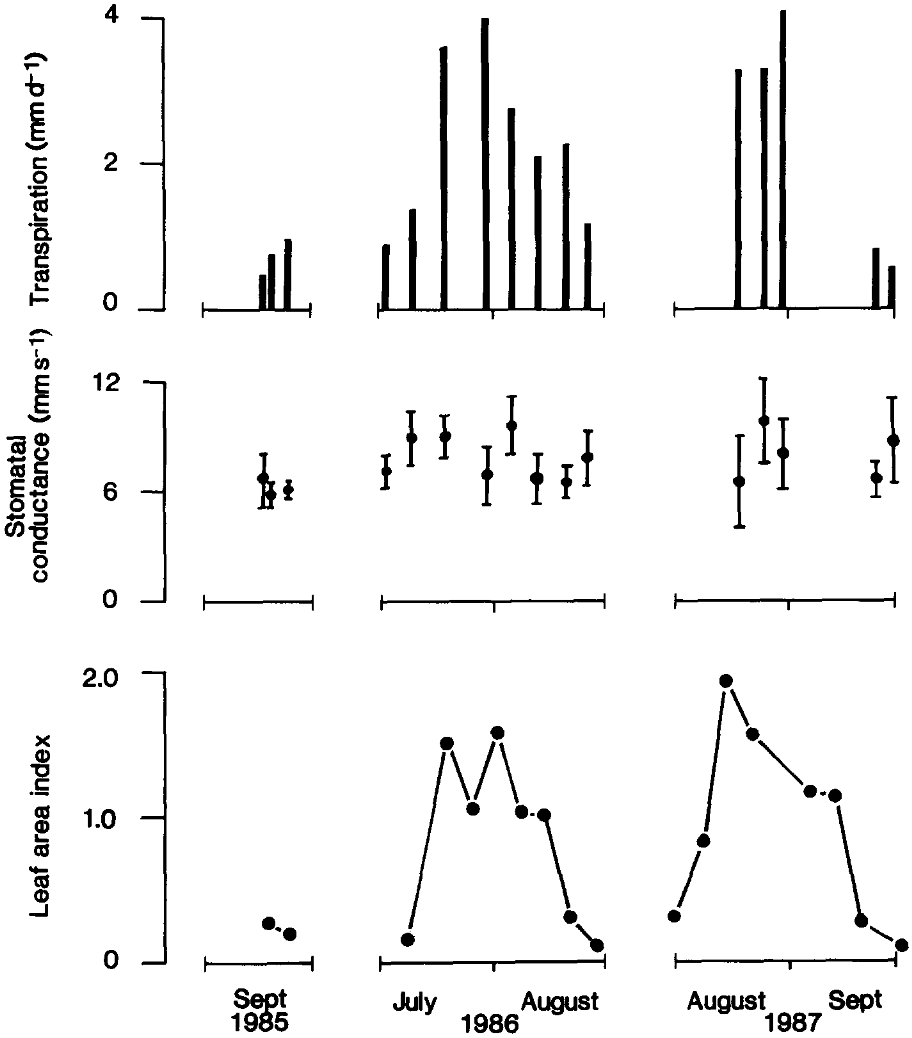

Fig. 6. Seasonal changes in daily total transpiration during 1985, 1986 and 1987. Concurrent values of midday (09:00–15:00 h) mean (± s.d.) stomatal conductance and leaf area index area also shown for comparison.

15 days during 1985, 1986 and 1987. Total daily evaporation varied from approximately 1.5 to 4.5 mm, depending on soil surface wetness and leaf area index. Soil evaporation accounted for anything between 5 and 80% of the total daily evaporation.

The total daily evaporation measured by the Hydra is plotted against the sum of the measured soil and plant evaporation in Fig. 9. Of the 14 days when comparison can be made, the agreement between the two estimates of daily

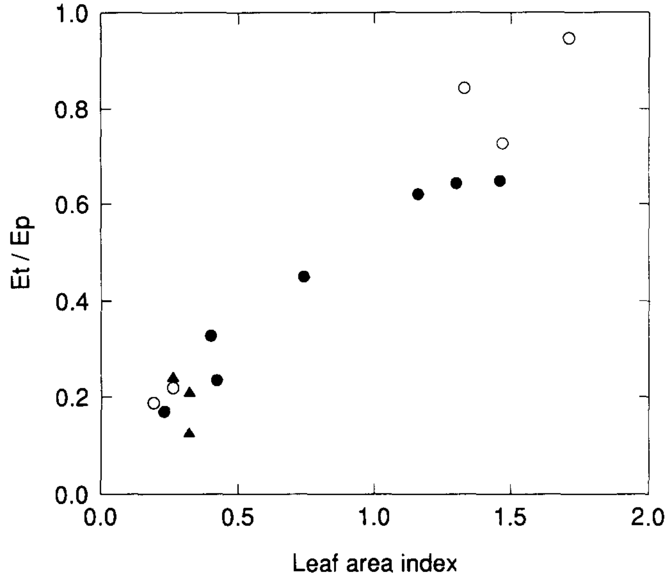

Fig. 7. The relationship between the ratio of daily total transpiration (E_t) to potential evaporation (E_p) as a function of leaf area index in 1985 (▲), 1986 (●) and 1987 (○).

total evaporation is good (difference is <15%) on 10 of the days. On the remaining 4 days the sum $E_s + E_t$ exceeds E_h by about 60% on average. Since the Hydra data show no concurrent systematic bias on the 4 days when the agreement is poor, the discrepancy is most likely to arise in the estimation of total evaporation by the porometry and lysimetry techniques. Furthermore, as the absolute value of soil evaporation is low on most of the days when there is a discrepancy, (e.g. 2 September 1987, Fig. 8(f)) it is not possible for it to be explained by over-estimation of soil evaporation. By default then we conclude that the most likely source of the disagreement shown in Fig. 9 is in the over-estimation of transpiration by the porometry technique when the leaf area index was comparatively high. Although the variance in g_s data is high (see Fig. 6) there is no systematic trend in these data which could account for such a large over-estimation of E_t. On the other hand, it is possible that the part of the field where samples were taken for leaf area index determination was atypically dense and gave an over-estimate of the field area average LAI. The Hydra gives an integrated total evaporation for a large part of the field (see Fig. 1) and is representative of the area average LAI. The over-estimation of LAI was particularly likely during 1987 when the erratic rainfall pattern produced quite variable crop cover and this is when most of the discrepancy between $E_s + E_t$ and E_h occurred (Fig. 9). This highlights a more general leaf area sampling problem which is particularly acute in heterogeneous sparse crops.

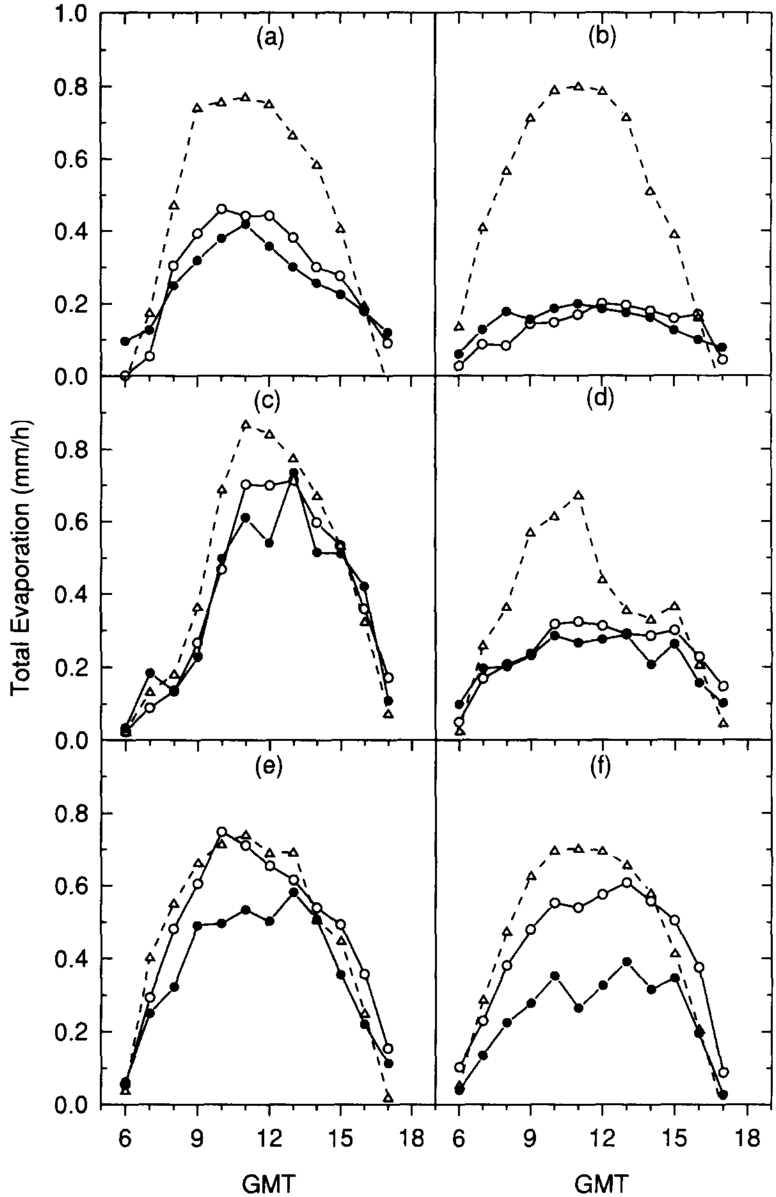

Fig. 8. A comparison of hourly fluxes of total evaporation as measured by the Hydra (●) with the sum of the measured soil and plant evaporation (○). Concurrent fluxes of net radiation (△) are also shown for comparison. Data are shown for 2 days with low LAI and (a) wet and (b) dry soil and 4 days with (c) high LAI and (e) wet and (d) dry and (f) soil.

TABLE 2

Summary of the comparison between total evaporation calculated using porometry and lysimeter data ($E_t + E_s$) and the MkII hydra. Penman potential evaporation, leaf and panicle area index and volumetric soil water content in the top 5cm of soil (Θ_s) are also shown for each day

DATE	Leaf and panicle area Index	Soil evaporation		Transpiration (mm)	Total evaporation		Potential evaporation (mm)	Θ_s (0–5 cm)
		% total	(mm)		$E_t + E_s$ (mm)	Hydra (mm)		
17 September 1985	0.32	80	2.5	0.6	3.1	2.8	4.9	0.09
19 September 1985	0.32	66	2.2	1.1	3.3	2.9	5.3	0.05
24 September 1985	0.26	14	0.2	1.4	1.6	1.7	5.7	0.01
2 July 1986	0.23	25	0.3	1.0	1.4	1.6[a]	6.0	n/a
9 July 1986	0.40	23	0.5	1.5	2.0	1.9[a]	4.7	0.03
30 July 1986	1.3	12	0.6	4.4	5.0	3.0	6.8	0.04
6 August 1986	1.5	37	1.8	3.0	4.8	4.5	4.6	0.07
13 August 1986	1.2	20	0.6	2.3	2.9	2.6	3.7	0.03
21 August 1986	0.74	22	0.7	2.6	3.3	3.7	5.7	0.05
27 August 1986	0.44	49	1.3	1.3	2.6	n/a	5.6	0.06
19 August 1987	1.7	5	0.2	3.6	3.8	2.2	3.8	n/a
26 August 1987	1.5	37	2.1	3.6	5.7	4.4	5.0	n/a
2 September 1987	1.3	9	0.5	4.5	5.0	2.9	5.4	n/a
25 September 1987	0.26	27	0.5	1.2	1.7	1.9	5.7	n/a
30 September 1987	0.19	30	0.4	1.1	1.5	1.8	5.7	n/a

[a]Calculated as *Rn–G–H*, (no evaporation data available)

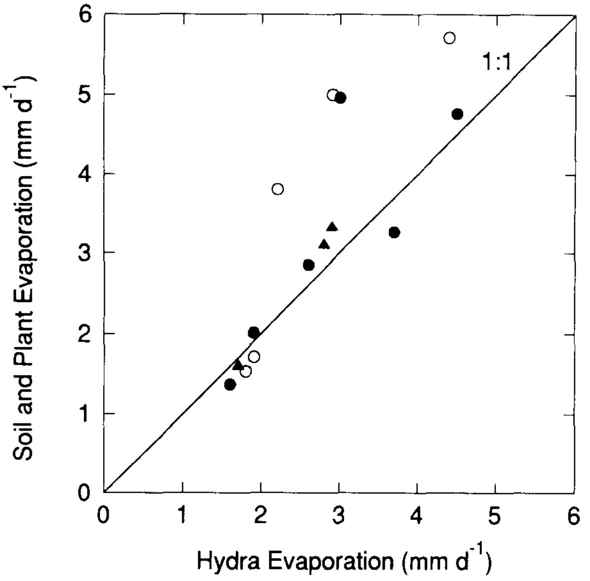

Fig. 9. A comparison of daily total evaporation as measured by the Hydra with the sum of the measured soil and plant evaporation in 1985 (▲), 1986 (●) and 1987 (○).

Figure 10 shows the complete set of 142 days total evaporation data measured using the Hydra during 1985, 1986 and 1987. Figure 10(c) shows that before the millet crop emerged, although the Penman potential evaporation was very high, 6–8 mm day^{-1}, the actual evaporation was generally low, approximately 0.5–1.0 mm day^{-1}, but this increased markedly in response to rainfall. As the rainy season got under way and the crop developed, potential evaporation declined and actual evaporation increased, but still varied between approximately 2.5 and 5.0 mm day^{-1}, Figs. 10(b) and 10(c). Towards the end of the crop season actual evaporation generally declined, as in 1985, Fig. 10(a). However, continued rainfall at this time of year can keep evaporation rates quite high, as in 1987, Fig. 10(c).

The ratio of actual to potential evaporation, E_h/E_p, is shown in Fig. 11 along with rainfall and leaf area index. To allow for the very different planting dates in the 3 years, the data are plotted against days after sowing (DAS). Pre-emergence values of E_h/E_p were extremely variable, 0.05 to 0.6, depending on rainfall, Fig. 11(c). As rainfall increased and leaf area developed, E_h/E_p increased but rarely exceeded 1.0. At maximum leaf area E_h/E_p oscillated between approximately 0.5 and 1.1, again depending on when rain fell, Figs. 11(b) and 11(c). The behaviour of E_h/E_p at the end of the crop season is also very dependent on the rainfall pattern. For example, in 1985 when the rains stopped abruptly around 90 days after sowing (DAS), E_h/E_p declined rapidly from 0.7 to 0.1 over a period of about 15 days, Fig. 11(a). In contrast,

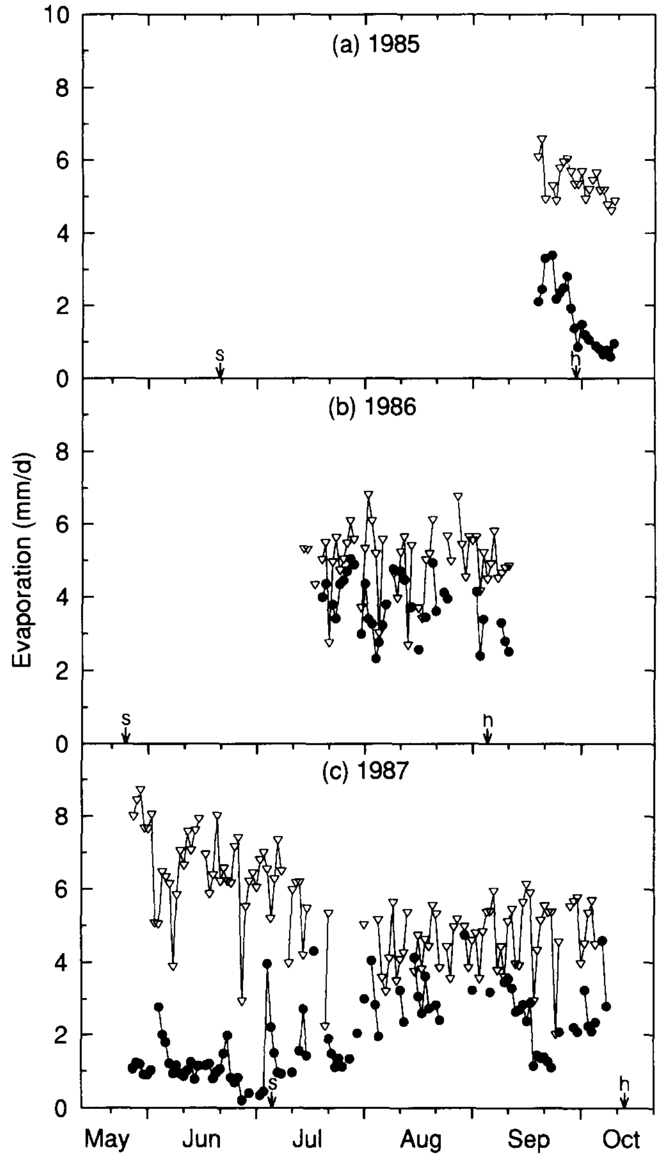

Fig. 10. Seasonal changes in daily total evaporation (●), as measured by the Hydra, and Penman potential evaporation (▿) during (a) 1985 , (b) 1986 and (c) 1987. Points are only joined on sequential days. Sowing (s) and harvest (h) dates in each year are also shown.

substantial rain fell between 80 and 100 DAS in 1986 (Fig. 11(b)) and in consequence E_h/E_p remained around 0.6. A period of drought between 60 and 80 DAS in 1987 produced a steady decline in E_h/E_p from approximately 1.0 to 0.2, with a parallel decrease in LAI, Fig. 11(c). Subsequent rainfall in-

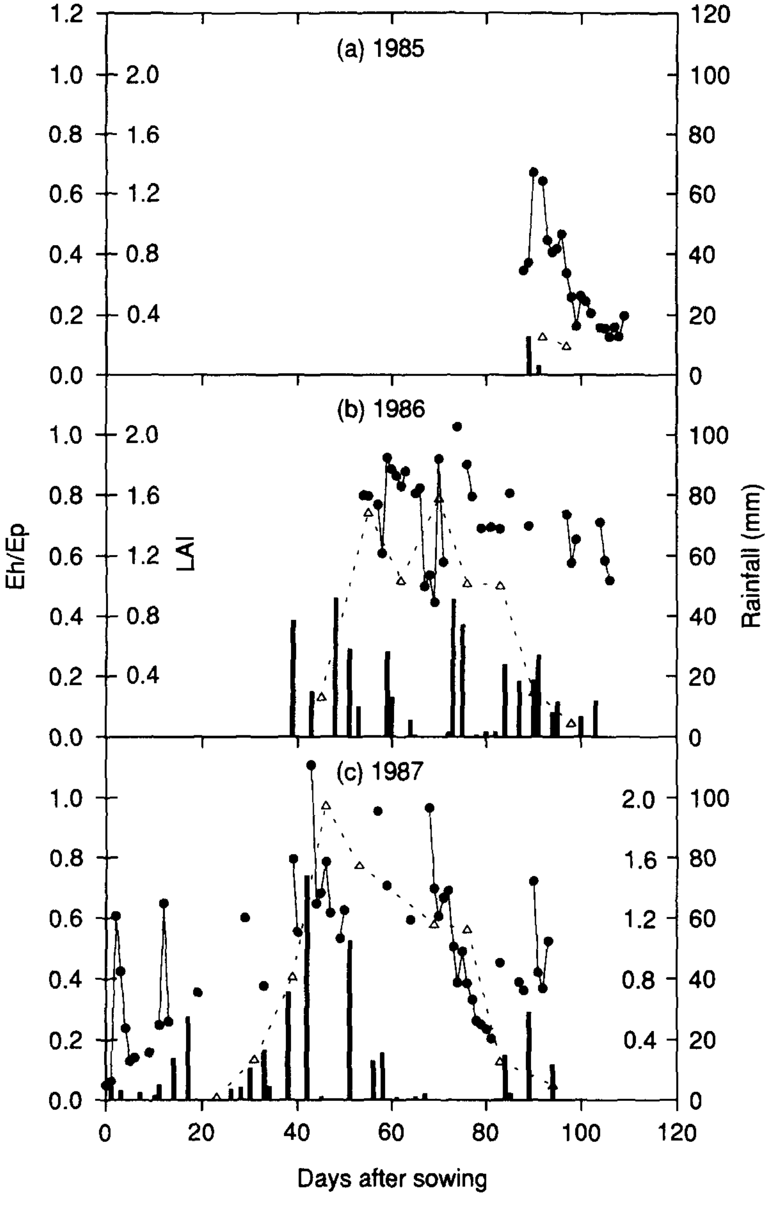

Fig. 11. The ratio of daily total actual/potential evaporation (E_h/E_p, ●) during (a) 1985, (b) 1986 and (c) 1987 as a function of days after sowing. Points are only joined on sequential days. For comparison rainfall and LAI (△) are also shown.

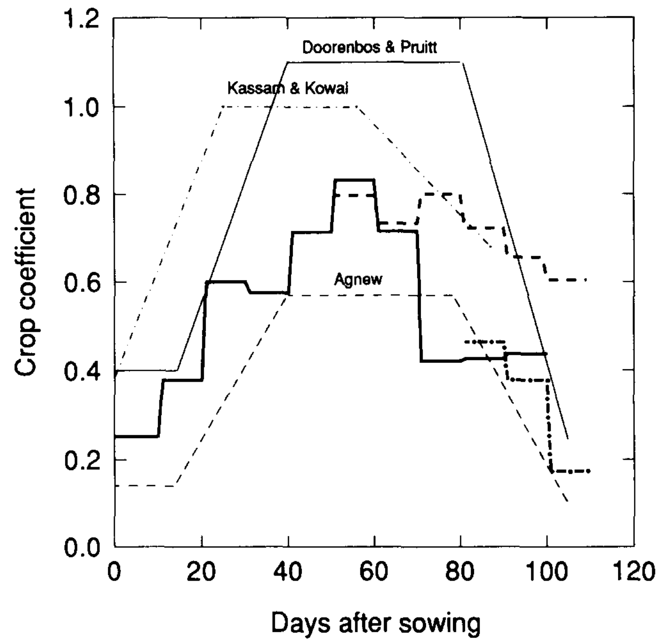

Fig. 12. A comparison of 10 day average crop coefficients calculated as the ratio E_h/E_p in 1985 (-·-·-), 1986 (— — —) and 1987 (———). For comparison the millet crop coefficients given by Agnew (1991), Kassam and Kowal (1975) and Doorenbos and Pruitt (1977) are also shown.

creased evaporation such that the ratio E_h/E_p recovered to approximately 0.5. The erratic behaviour of E_h/E_p underlines the difficulty of applying the simple crop factor approach of Doorenbos and Pruitt (1977) for estimating evaporation from rainfed millet in Niger. This is emphasised in Fig. 12 where 10 day average values of the crop coefficient (E_h/E_p) are plotted for the 3 years 1985, 1986 and 1987. Even when 10 day averages are used, it is clear that the value of crop coefficient can vary markedly depending on the rainfall (e.g. compare the period 70–80 DAS in 1986 and 1987). The crop coefficients calculated here are also very different from those reported for millet by Kassam and Kowal (1975), Doorenbos and Pruitt (1977), and Agnew (1991).

CONCLUSIONS

The data presented in this paper clearly demonstrate the importance of the soil evaporation component of the total water loss from millet. Depending largely on soil surface wetness, soil evaporation can range from the dominant to the almost insignificant term in total evaporation. On the soil type studied the decline in the rate of soil evaporation is very rapid, and most of the significant loss occurs in the first couple of days after rain. This implies that any model of soil evaporation should concentrate on correct prediction of the loss rates within this time period. Simple relationships between the cumulative soil evaporation and the square root of time since the last rain (e.g. Ritchie, 1972) may give a sufficiently accurate prediction, provided the proportionality constant is determined in situ for the soil in question. Monteith (1981) suggested that soil evaporation could also be modelled using the concept of a soil resistance, based on the idea that evaporation occurs from wet soil below a progressively deepening dry layer. Choudhury and Monteith (1988) showed that this concept also leads to the prediction that cumulative soil evaporation is proportional to the square root of time, in agreement with Ritchie (1972) and many other studies of the water loss from drying soils. No models have been fitted to the data in this paper since further analysis is being carried out to assess the relative merits of these different soil evaporation modelling schemes.

Preliminary estimates of evaporation from the sandy soil at Sadoré have been made by Wallace et al. (1989) and these have led to predictions of the total seasonal soil evaporation of about 200 mm in an average year, or approximately 35% of rainfall (Wallace, 1991). Similar proportions of rainfall are predicted as being lost as soil evaporation in the millet models of Bley et al. (1991) and Fechter et al. (1991). In wheat grown in northern Syria by Cooper et al. (1983), again about a third of rainfall was lost as soil evaporation with even greater losses (50–60% of rainfall) in dryland barley. One of the principal challenges in improving these types of crop is to find ways of reducing this loss of water and increasing the proportion of rainfall used as transpiration. Some of the more promising approaches to this appear to lie in mixed plant communities such as intercrops and agroforestry where increased ground cover may reduce soil evaporation and runoff. In those semi-arid areas where water limits production, increased efficiency of rainfall utilization by complementary species has the potential to increase total yield.

Transpiration from millet appears to be more strongly controlled by leaf area than stomatal conductance. Stomatal conductances measured in this study were generally high throughout a range of soil moisture conditions and are also comparable with g_s values observed in other studies of millet (see Wallace et al., 1990). The implication is that millet does not tend to conserve moisture, rather that it transpires freely as long as the root system can supply the water to meet atmospheric demand. Periods of soil moisture stress may be dealt with by reducing leaf area via leaf senescence or tiller mortality. This kind of behaviour may make the modelling of millet transpiration comparatively simple. It may be sufficient to specify a fixed hourly or daily average leaf stomatal conductance and the leaf area index, rather than using a more complex model where g_s is a function of climatic and soil variables (e.g. as in Jarvis 1976). An alternative to this would be to use the relationship between E_t/E_p and LAI defined in Fig. 7. This relationship is likely to be curved rather than linear since it was concluded that the E_t data from 1987 is probably an over-estimate. A curved relationship is also what would be predicted by considering the radiation interception of the canopy increasing exponentially according to Beer's law. Indeed curved relationships between E_t/E_p and LAI have already been reported in other crops by Feddes (1987) and Ritchie and Johnson (1990).

The comparison of total evaporation as measured by the Hydra and as the sum of soil and plant evaporation was generally very good, giving some confidence in the different methods used. There remains the discrepancy at high leaf area indices, which is thought to be a result of over-estimation of LAI, owing to poor sampling in a very heterogeneous canopy. However, the possibility cannot be ruled out that the combination model used to calculate transpiration over-estimates E_t at high LAI in this climate. Over-estimation of E_t using the same model has also been reported by Nichols (1992) in sparsely vegetated rangeland when the soil surface was dry. The problem appears to lie in the specification of the within and above canopy aerodynamic conductances (Ham and Heilman, 1991) and the difficulty of applying a one dimensional model in very sparse canopies (Graser et al., 1987). Further tests of the Shuttleworth–Wallace approach under appropriate conditions are required to investigate this further.

The final section of this paper showed how total actual evaporation was very variable from day to day, largely as a function of climatic demand, soil wetness and LAI. The ratio of evaporative supply to demand, as indicated by E_h/E_p, was also very variable and since this is a measure of the crop coefficient (Doorenbos and Pruitt, 1977), it is therefore unlikely that this simple approach will work effectively for this type of crop, even when 10 day averages are used. Agnew (1991) also reports crop coefficients for millet which are much more erratic than the smoothed behaviour prescribed by the Doorenbos and Pruitt method. In sparse rainfed crops, where soil evaporation plays an important role, crop coefficients are clearly very difficult to apply since there value will be dependent on the antecedent rainfall conditions. In recognition of this problem Ritchie and Johnson (1990) describe a scheme where crop coefficients are adjusted according to the time since the last rainfall. However, this is simply confounding the problem since this leaves the crop coefficient as a complex mixture of not only the surface and aerodynamic properties of the soil and crop, but also the climate in which they are derived (Shuttleworth, 1993).

Although simple models may be desirable, the minimum requirement for successful prediction of sparse crop evaporation is the explicit recognition of the separate soil and plant components. These can be treated in an interactive mode, where the fluxes from the soil and plants can affect one another, as in the Shuttleworth and Wallace (1985) model, or alternatively in an non-interactive mode, as in the Ritchie (1972) model. The importance of the quantitative difference between the two approaches will depend on the application. In operational applications such as the yield prediction schemes used by the Food and Agriculture Organization (FAO) (Frère and Popov, 1979), a major advantage of using a model where E_t and E_s are specified separately is that in sparse crops E_t is much more closely related to yield than total evaporation (Tanner and Sinclair, 1983). Yield predictions based on E_t should therefore be more reliable. More accurate models of millet evaporation would also improve hydrological water balance models in arid regions.

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REFERENCES

Agnew, C.T., 1982. Water availability and the development of rainfed agriculture in south-west Africa. Trans. Inst. Br. Geogr. N.S., 7: 419–457.

Agnew, C.T., 1991. Evaluation of a soil water balance model for the analysis of agricultural drought in the Sahel. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and C. GirouxSoil (Eds.), Water Balance in the Sudano-Sahelian Zone. Proc. Niamey Workshop, February 1991, IA HS Publ. no. 199, pp. 583–592.

Azam-Ali, S.N., 1983. Seasonal estimates of transpiration from a millet cropusing a porometer. Agric. For. Meteorol., 30: 13–24.

Bley, J., van der Ploeg, R.R., Sivakumar, M.V.K. and Allison, B.E., 1991. A risk-probability map for millet production in southwest Niger. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and C. Giroux (Eds.), Soil Water Balance in the Sudano-Sahelian Zone. Proc. Niamey Workshop, February 1991. IAHS Publ. no.199, pp. 571–581.

Choudhury, B.J. and Monteith, J.L., 1988. A four-layer model for the heat budget of homogeneous land surfaces. Q. J. R. Meteorol. Soc., 114: 373–398.

Cooper, P.J.M., Keatinge, J.D.H. and Hughes, G., 1983. Crop evapotranspiration—a technique for calculation of its components by field measurements. Field Crop Res., 7: 299–312.

Dolman, A.J. and Wallace, J.S., 1991. Lagrangian and K-theory approaches in modelling evaporation from sparse canopies. Q. J. R. Meteorol. Soc., 117: 1325–1340.

Doorenbos, J. and Pruitt, W.O., 1977. Crop Water Requirements. FAO Irrigation and Drainage Paper 24, FAO, Rome.

Fechter, J., Allison, B., Sivakumar, M.V.K., van der Ploeg, R.R. and Bley, J., 1991. An evaluation of the SWATRER and CERES–Millet models for southwest Niger. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and C. Giroux (Eds.), Soil Water Balance in the Sudano-Sahelian Zone. Proc. Niamey Workshop, February 1991. IAHS Publ. no. 199, pp. 505–513.

Feddes, R.A., 1987. Crop factors in relation to Makkink reference—crop evapotranspiration. In: J.C. Hooghart (Ed.), Evaporation and weather: Technical meeting 44, Ede, 25 March 1987, Netherlands. Proceedings and information/TNO Committee on Hydrological Research; no. 39, pp. 33–45.

Frère, M. and Popov, G.S., 1979. Agro-meteorological crop monitoring and forecasting. Plant Production and Protection Paper No. 17, FAO, Rome.

Gash, J.H.C., 1986. A note on estimating the effect of a limited fetch on micro meteorological evaporation measurements. Boundary-Layer Meteorol., 35: 409–413.
Graser, E.A., Verma, S.B. and Rosenberg, N.J., 1987. Within-canopy temperature patterns of sorghum at two row spacings. Agric. For. Meteorol., 41: 187–205.
Ham, J.M. and Heilman, J.L., 1991. Aerodynamic and surface resistances affecting energy transport in a sparse crop. Agric. For. Meteorol., 53: 267–284.
Jarvis, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Phil. Trans. R. Soc. (Lond). Series B, 273: 593–610.
Kassam, A.H. and Kowal, J.M., 1975. Water use, energy balance and growth of Gero millet at Samaru, northern Nigeria. Agric. Meteorol., 15: 333–342.
Monteith, J.L., 1981. Evaporation and surface temperature. Q. J. R. Meteorol. Soc., 107: 1–27.
Nichols, W.D., 1992. Energy budgets and resistances to energy transport insparsely vegetated rangeland. Agric. For. Meteorol., 60: 221–147.
Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc., A193, 120–145.
Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res., 8: 1204–1213.
Ritchie, J.T. and Johnson, B.S., 1990. Soil and plant factors affecting evaporation. In: B.A. Stewart and D.R. Neilsen (Eds.), Irrigation of Agricultural crops — Agronomy Monograph no. 30.), ASA, CSSA, and SSSA, Madison, WI, pp. 363–390.
Shuttleworth, W.J., 1993. Evaporation. In: D.R. Maidment (Ed.), Handbook of Hydrology. McGraw-Hill, New York. (In Press).
Shuttleworth, W.J. and Wallace, J.S., 1985. Evaporation from sparse crops-an energy combination theory. Q. J. R. Meteorol. Soc., 111: 839–855.
Shuttleworth, W.J. and Gurney, R.J., 1990. The theoretical relationship between foliage temperature and canopy resistance in sparse crops. Q. J. R. Meteorol. Soc., 116: 497–519.
Shuttleworth, W.J., Gash, J.H.C., Lloyd, C.R., McNeill, D.D., Moore, C.J. and Wallace, J.S., 1988. An integrated micrometeorological system for evaporation measurement. Agric. For. Meteorol., 43: 295–317.
Sivakumar, M.V.K., 1987. Climate of Niamey. Progress Report-1, ICRISAT Sahelian Center, Niamey, Niger. International Crops Research Institute for the Semi-Arid Tropics, 36 pp.
Strangeways, I.C., 1972. Automatic Weather Stations for network operation. Weather, 27: 403–408.
Tanner, C.B. and Sinclair, T.R., 1983. Efficient water use in crop production: Research or Re-Search? In: H.M. Taylor, W.R. Jordan and T.R. Sinclair (Eds.), Limitations to Efficient Water Use in Crop Production.), ASA, CSSA, and SSSA, Madison, WI, pp. 1–27.
Wallace, J.S., 1991. The measurement and modelling of evaporation from semiaridland. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and C. Giroux (Eds.), Soil Water Balance in the Sudano–Sahelian Zone. Proc. Niamey Workshop, February 1991, IAHS Publ. no. 199, pp. 131–148.
Wallace, J.S., Gash, J.H.C., McNeil, D.D., LLoyd, C.R., Oliver, H.R., Keatinge, J.D.H. and Sivakumar, M.V.K., 1989. Measurement and prediction of actual evaporation from sparse dryland crops. ODA Report no. ODG 89/1, Institute of Hydrology, Wallingford, 39 pp.
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. Agric. For. Meteorol., 51: 35–49.
West, L.T., Wilding, L.P., Landeck, J.K. and Calhoun, F.G., 1984. Soil survey of theICRISAT Sahelian Center, Niger, West Africa. Soil and Crop Sciences Department/Tropsoils, Texas A & M, 66 pp.