ELSEVIER

Agricultural Water Management 27 (1995) 225–242

Agricultural water management

The impact of sparse millet crops on evaporation from soil in semi-arid Niger

Carl C. Daamen [a,*], L.P. Simmonds [a], M.V.K. Sivakumar [b]

[a] Department of Soil Science, University of Reading, Whiteknights, P.O. Box 233, Reading RG6 2DW, UK

[b] ICRISAT Sahelian Center, B.P. 12404, Niamey, Niger

Accepted 3 November 1994

Abstract

Direct evaporation from soil is an important component of crop water balances in semi-arid environments. The effects of a crop and of crop management on this water loss from the soil have been estimated in the past using combinations of field measurement and simple models, but there are inconsistencies in the conclusions reached.

This paper presents data from water balance studies on millet crops in Niger during the 1991 and 1993 seasons. Evaporation from soil (E_s) was measured under two contrasting cropping intensities in both years using the microlysimeter method. Small seasonal reductions in E_s from the higher intensity crop were recorded (12% and 16% in 1991 and 1993, respectively). Significant reductions in daily E_s were: (1) nearly all recorded within a limited period in the season when there were large differences in transpiring leaf area; (2) recorded for both high (> =2 mm day^{-1}) and low (<0.8 mm day^{-1}) values of E_s. These data indicate that soil drying by root water uptake contributed to the reduction of E_s. Increased shading of the soil by the crop canopy does not result in a proportional reduction of E_s.

Two simple models for estimating E_s beneath crops (Ritchie, 1972; Cooper et al., 1983) are compared with field data and an improvement to the Ritchie model is suggested. Two new parameters are introduced to estimate the relative importance of (1) the atmospheric vapour pressure deficit to potential evaporation and (2) root water uptake to soil drying. The brief description of environment and crop included in the new approach allows identification of the environments in which there is scope for substantial reduction in E_s through crop management.

Keywords: Evaporation; Crop water balance; Pearl millet; Soil evaporation; Model; Microlysimeters

1. Introduction

Evaporation from the soil surface (E_s) can be a major component of crop and soil water balance. In semi-arid environments, some estimates of seasonal E_s beneath annual crops are

* Corresponding author. Tel. +44 1734 318911, Fax. +44 1734 316660, Email. c.c.daamen@reading.ac.uk.

SSDI 0378-3774(95)01157-9

in excess of 50% of seasonal rainfall (Allen, 1990; Papendick and Campbell, 1990; Pilbeam et al., 1995). If this large proportion of rainfall (E_s) could be decreased and used (at least in part) as transpiration from a crop, an increase in crop yield and seasonal water use efficiency would be expected (Cooper et al., 1987). The potential benefit of reducing evaporation from the soil surface has long been recognised (Lemon, 1956; Penman, 1941). Some success in achieving a reduction in E_s with intensified crop management (e.g. narrower row spacing and application of fertilizer) has been attributed to reduced solar radiation penetration to the soil surface beneath a crop canopy (Adams et al., 1976; Cooper et al., 1983). However, two recent studies in dry mediterranean environments (Allen, 1990; Yunusa et al., 1993a) suggest that a reduction in radiation incident at the soil surface has little or no effect on E_s. Furthermore, the effect of root water uptake on E_s is beginning to be considered (Allen, 1990).

To assess the value of crop management practices in the reduction of E_s, E_s must be accurately measured or estimated. The microlysimeter method (Boast, 1986) is a popular approach at present, but it is impractical to measure E_s continuously throughout a crop season because frequent replacement of soil cores is required (Daamen et al., 1993) and measurements are invalid if interrupted by rainfall (Allen, 1990). Thus, seasonal estimation of E_s requires application of a model to either supplement direct measurements (Allen, 1990; Yunusa et al., 1993b) or largely replace the need for measurement (e.g. Ritchie, 1972; Cooper et al., 1983).

This paper presents data from water balance studies on pearl millet crops (*Pennisetum glaucum* (L.) R.Br.) in Niger during the 1991 and 1993 seasons. Evaporation from soil was measured using microlysimeters under two different cropping intensities in both years. Two models for estimating E_s are compared with field data and some components of an improved model are developed. The new modelling approach offers an explanation of the apparent contradiction in the results of previous studies regarding the effectiveness of management practices in modifying crop water use efficiency. This approach is also used to identify the environments in which there is scope for substantial reduction in E_s through crop management.

1.1. Models of evaporation from soil

A classical approach to modelling evaporation from an initially wet soil profile begins with the hypothesis that evaporation occurs in two (or three) distinct and consecutive stages (see Hillel, 1980; Hanks and Ashcroft, 1980; Marshall and Holmes, 1988; Jury et al., 1991). In the first stage, evaporation (E_s) is limited by the movement of water from the soil surface into the atmosphere, and in the second stage, E_s is limited by the movement of water through the soil to the surface. Such approaches are founded on a theoretical solution of water loss from soil which assumes a constant evaporative demand (no diurnal variation) and an initial soil water content that is the same at all depths. Under field conditions, in which there is a large diurnal variation in evaporative demand and often steep gradients in soil water content with depth, this approach may well be inadequate.

Ritchie (1972), used the two-stage evaporation model to estimate daily E_s beneath a developing crop which was not water stressed. Ritchie's approach has been widely adopted in crop water balance studies (e.g. Shouse et al., 1982; Dierckx et al., 1986; Villalobos and

Fereres, 1990). Beginning with an initially wet condition, Ritchie assumed that the first stage of evaporation continues until a certain volume of water (U, mm) has been evaporated from the soil. During this stage, evaporation beneath a crop was deemed to occur at a potential rate which is a fraction (equal to the proportion of solar radiation that penetrates to the soil surface) of the potential rate for bare soil. The validity of this assumption is discussed later. The potential evaporation from soil beneath a crop canopy (E_{pc}, mm) was calculated using the leaf area index (L), an extinction coefficient (K) and a 'bare soil' potential evaporation (E_{pR}, mm) as:

$$E_{pc} = E_{pR}\exp(-KL)$$
$$E_{pR} = [\Delta/(\Delta+\gamma)]R_{no} \tag{1}$$

where R_{no} is the daily net radiation, Δ is the slope of saturation vapour pressure vs. temperature curve at mean air temperature, γ is the psychometric constant (Ritchie, 1972). A typical value of K for millet in Niger is 0.41 (Wallace et al., 1990). Using this approach the presence of a crop canopy lengthens the first stage of evaporation because evaporation is slower than that from a bare soil. In the second stage, Ritchie's approach assumed a crop has no influence on evaporation from soil. During the second stage, cumulative evaporation ($\Sigma E_{s,2}$) was proportional to the square root of time since the start of the second stage (t_2, days) such that:

$$\Sigma E_{s,2} = \alpha\sqrt{t_2} \tag{2}$$

where α is a constant for a given soil.

It should be noted that a strict system of accounting for water fluxes was adopted by Ritchie (1972). An implicit assumption of this approach is that the soil water content controls the movement of water to the soil surface and this water content is a function of time or ΣE_s only. The effect of root water uptake on soil water content is assumed negligible, although this might be a major loss of water from the surface layers.

The second modelling approach considered here is an empirical model suited to a crop environment in northern Syria (Cooper et al., 1983). No explicit first and second stages are used, although the first day after rain is effectively a first stage. The daily evaporation from soil beneath a canopy is determined by the number of days since rain, t, and the crop green area index G as:

$$E_s = E_{pC}\frac{\exp(-KG)}{t} \tag{3}$$

where E_{pC} is the daily potential evaporation, which was estimated from pan evaporation measurements by Cooper et al. (1983). Both E_{pC} and G influence the estimate of evaporation throughout the drying cycle. This is in contrast with the approach of Ritchie (1972) in which these factors only influence E_s during the first stage of evaporation. Although Cooper et al. (1983) use G (green area index) and not total leaf area index, their discussion does not indicate that this was intended to account for root water uptake/transpiration in any way: it was only used to make allowance for interception of radiant energy by the crop canopy and in this respect is analogous to the use of L by Ritchie (1972).

2. Materials and methods

Measurements of evaporation from soil were made at the ICRISAT Sahelian Center, Sadoré, Niger during the rainy season in 1991 and 1993. The sites used in 1991 and 1993 were close to each other and both were within the same area classified as 'Labucheri Sand', a Psammentic Paleustalf (West et al., 1984). Using the FAO soil classification system the soil is a Luvic Arenosol (Swindale, 1982). The soil particle size distribution in the A horizon is typically 91% sand (2.0–0.05 mm), 5% silt (0.05–0.002 mm) and 4% clay (< 0.002 mm) (West et al., 1984). The soil profile is deep (approximately 5 m) and there is no water table present.

The climate is dominated by a single rainy season and is typical of the semi-arid tropics. Potential evaporation is high and rainfall erratic at the beginning of the season (see Sivakumar, 1987, or Wallace et al., 1993, for further details). Rainfall for the two years is shown in Fig. 1.

Use of the microlysimeter method in this environment was discussed by Daamen et al. (1993). Briefly, soil cores were extracted within an experimental plot and mounted flush with the soil surface in outsized lining tubes which had been permanently located in undisturbed areas of the plot. In both 1991 and 1993, soil cores were only used to record evaporation from soil for approximately 1 day following the morning of extraction from the soil profile. In both years microlysimeters were 100 mm deep. Internal diameters were 152 mm and 51 mm in 1991 and 1993, respectively. Daamen et al. (1993) reported no significant difference in evaporation recorded using microlysimeters of these two diameters. Microlysimeters were weighed to the nearest 1 g (1991) or 0.01 g (1993).

Microlysimeter data were carefully screened to exclude data from soil cores that were older than 1.5 days at the end of the measurement period, and to exclude measurement

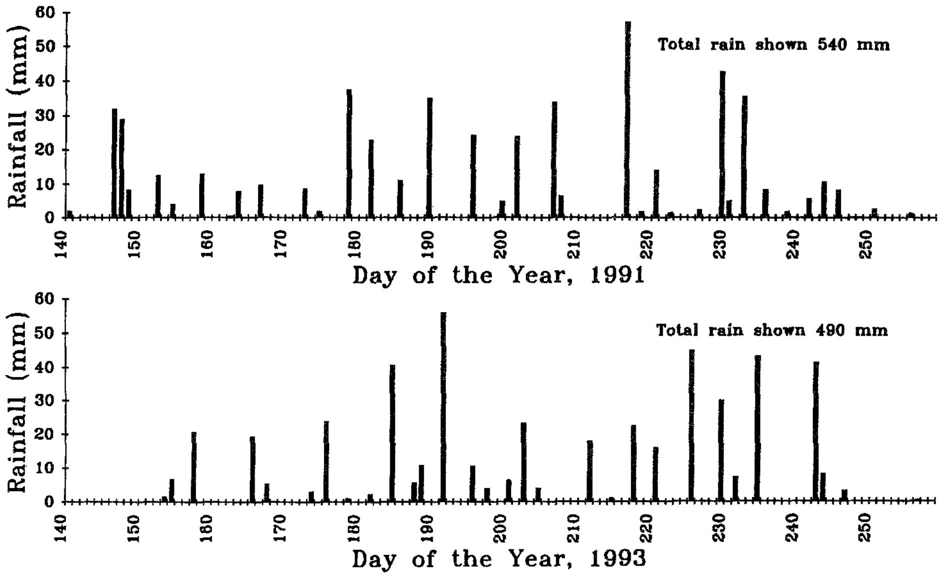

Fig. 1. Daily rainfall at Sadoré, Niger, during the 1991 and 1993 growing seasons. Prior to Day 140, only 45 mm and 8 mm fell in 1991 and 1993 respectively.

periods in which rain fell. This approach minimised the errors inherent in the method allowing differences between cropped and bare plots to be detected reliably (Daamen et al., 1993).

2.1. Experimental design

In both years the experimental plots contained two treatments arranged in a randomised block design. The treatment details in the two years are given below. Millet is sown in pockets (i.e. holes) which hold 2–3 plants after thinning. Samples for crop growth analysis were taken in four blocks at ten day intervals. Within each plot two millet pockets were taken as a sample. A leaf area meter (LI-COR, Lincoln, NE) was used to determine specific green leaf area of two of the four replicates. Plants were divided into leaves, stems and panicles for dry matter analysis. Leaf area index in the field was calculated from oven-dry leaf weights, specific leaf area, and a count of millet pocket survival.

1991 Trial

In 1991, E_s was measured in two different crop management systems. The first resembled a traditional crop management system using the following components: flat uncultivated soil; local pearl millet variety (cultivar Sadoré Locale); plants sown on an irregular grid at approximately 6000 pockets ha^{-1} with three plants per pocket after thinning; no applied fertilizer. The improved management system used the following components: ridge/furrow cultivation; improved pearl millet variety (cultivar CIVT); ridges were separated by 0.75 m and millet sown along the ridge at 1.3 m spacing giving 10 000 pockets ha^{-1} and after thinning three plants per pocket; fertilizer was applied at rates of 45 kg N ha^{-1} and 45 kg P ha^{-1}. Both systems were sown with millet on day of year (Day) 146, 1991. The crops were harvested on Day 239 (improved) and Day 274 (traditional).

Two transects of three microlysimeters were used to measure E_s in the Traditional cropping system. Lining tubes were located at equal distances along the diagonal between two neighbouring millet pockets within one of the replicate blocks. In the improved system, three transects of two microlysimeters were used (one on the ridge and the other beside it in the furrow). The plot size was 10 m × 10 m. Soil cores were extracted from within the plots containing lining tubes or from appropriate plots in neighbouring blocks. Soil cores were taken along transects at the same positions as lining tubes and transects were randomly located within a plot.

1993 Trial

In 1993 the differences in cropping intensity between the two systems monitored were much larger than in 1991. The millet was flat planted to simplify the measurement of E_s. The high density crop system had the following components: improved variety of millet cultivar CIVT (as in 1991); planted on a square grid at 30 000 pockets ha^{-1} with three plants per pocket after thinning; fertilizer was applied (30 kg P ha^{-1}; 68 kg N ha^{-1}). Evaporation from soil in this high density millet crop was compared with flat bare soil. The millet was sown on Day 165, and harvested on Day 257. Plot size was 13 m × 13 m.

Use of small-diameter microlysimeters (i.d. 51 mm) in 1993 permitted an increased number of replications. E_s measurements were made in three blocks. Four soil cores were extracted from the soil profile and mounted within each plot giving a total of 24 microlysimeters for each day of measurement. Soil cores were taken in pairs, one within 0.23 m of a pocket and the other beside the same pocket but outside this area. The pairs of soil cores were randomly located in the plot.

2.2. Meteorological and soil water measurements

Meteorological measurements at the experimental site included rainfall, air temperature, air humidity and windspeed which were averaged over 30 min intervals in both years. In 1993, net radiation was recorded over the bare soil and the high density cropping treatment. Soil water content was measured using a neutron probe (IH2, Didcot Instrument, Abingdon, UK) at two locations within each high density crop plot and at one location within bare plots in 1993. A field calibration of the neutron probe was carried out at the site for depths 0.1 m, 0.2 m and 0.3 m or greater. Average profile water contents from 0.05–0.9 m were determined from six access tubes (i.e. 3 blocks × 2 tubes) in the high density crop and five tubes in bare soil.

Potential evaporation (E_p, mm) over a period was taken to be a sum of half-hourly rates, E_h (mm s^{-1}), calculated assuming bare soil conditions as:

$$\lambda E_h = \frac{\Delta}{\Delta + \gamma}(R_n - G_s) + \frac{\rho c_p}{\Delta + \gamma}(D/r_a) \tag{4}$$

where λ is the latent heat of vaporization (J kg^{-1}), Δ is the slope of saturation vapour pressure verses temperature curve (kPa K^{-1}), γ is the psychometric constant (kPa K^{-1}), ρc_p is the volumetric specific heat of air (J m^{-3} K^{-1}), R_n is the net radiation over bare soil (W m^{-2}), G_s is the ground heat flux, positive downward (estimated as $0.2R_n$) (W m^{-2}), D is the vapour pressure deficit of the air (kPa), see Monteith and Unsworth (1990). The aerodynamic resistance of the atmosphere, r_a (s m^{-1}), was calculated assuming neutral conditions as:

$$r_a = \frac{(\ln[(z-d)/z_0])^2}{k^2 u} \tag{5}$$

where z is the height of measurement of wind, air temperature and air humidity (2.5 m), d is the zero plane displacement (insignificant here), z_0 is the roughness length for the soil surface (0.01 m), k is the von Karman constant (0.41), u is the wind speed at height z (m s^{-1}). Calculation of E_p allows comparison of atmospheric demand on bare soil with the measured evaporation during the period. The accuracy of E_p will be affected by the estimate of G_s, fetch requirements and air buoyancy effects on r_a, however it should still provide a reasonable indication of evaporative demand.

The first term on the right hand side of Eq. 4 is referred to as the radiation term and the second term as the aerodynamic term later in the text.

3. Results

Fig. 2 shows the development of green leaf area index (G) in both cropping systems for both years. Differences in G between the two treatments were larger than 0.5 from about Day 193 to 212 in 1991 and from Day 196 to 250 in 1993.

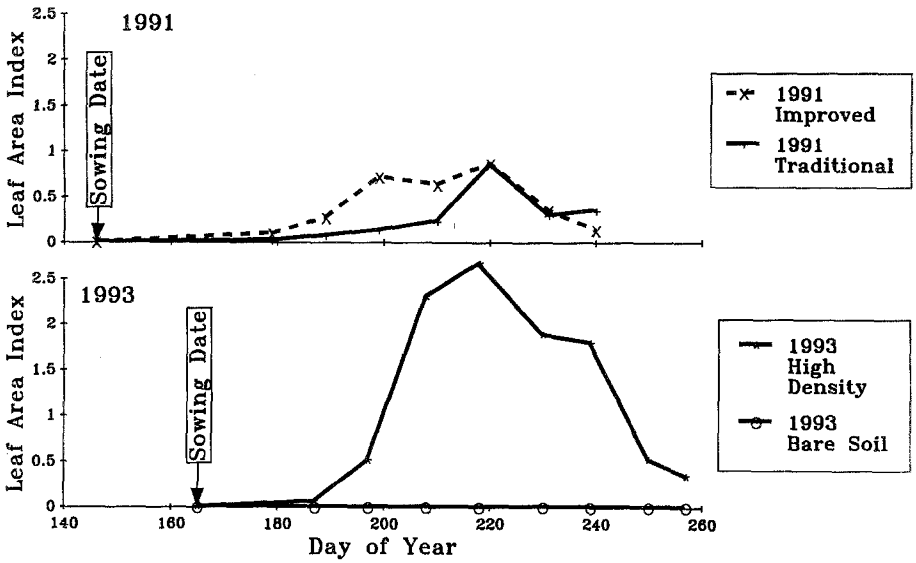

Fig. 2. Green leaf area indices for both treatments in 1991 and 1993.

To test for significant difference in evaporation from soil (E_s) between treatments in either 1991 or 1993, analysis of variance in E_s data for all measurement days was used. This analysis assumes the data are spatially independent. Lascano and Hatfield (1992) found no spatial structure in E_s data from microlysimeters on flat bare soil down to a separation of 1 m. To achieve homogeneity of variance a square root transformation of E_s data was required in 1991 and a log transformation in 1993 (Lascano and Hatfield, 1992, noted both lognormal and normal distributions of E_s). Also, contrast analysis of the 1991 data revealed that differences between the Traditional system and the Improved system contributed more to the variance than differences between the ridge and the furrow within the Improved system.

Figs. 3 and 4 show the average daily E_s from one treatment plotted against the other for 1991 and 1993, respectively. The difference in treatment means is larger than twice the standard error for points outside the two broken lines drawn on these figures (i.e. they are significantly different at $P = 0.05$). In both years there was a significant interaction between the effect of the treatment and the measurement date (i.e. the treatment effect was not the same on all days). It is clear from Figs. 3 and 4 that overall the presence of a denser crop (the Improved and the High Density Millet respectively) caused a reduction in evaporation from soil. Cumulative totals of measured evaporation from soil in 1991 and 1993 are presented in Table 1.

Table 2 gives details of the 1993 data set. Green leaf area index of the crop on any particular day was determined by linear interpolation between days of measurement. Similarly, linear interpolation was used to determine the difference in average water content of the bare soil profile (θ_b) and the cropped profile (θ_c) from 0.05 m to 0.90 m. The significance of difference in treatment means is included to show the grouping of significant differences over the season. Details particular to specific days in Table 2 follow: (1) on Days 187 and 191, E_s measurements were made in only one of the three blocks; (2) on Day 204 evapo-

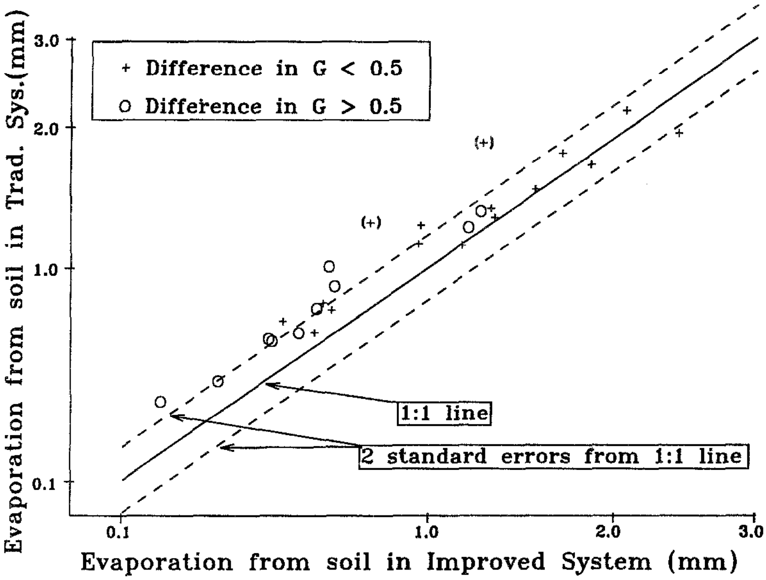

Fig. 3. A comparison of evaporation from soil measured in the improved and in the traditional treatments, 1991. Days of measurement when the difference in green leaf area index (G) values between treatments >0.5 are indicated by open circles, days when the difference in $G<0.5$ are indicated by crosses. The two measurement days in parentheses immediately preceded the period in which the difference in $G>0.5$. Points lying outside the bounds of the dashed lines indicate differences in treatment means are significant at the 5% level.

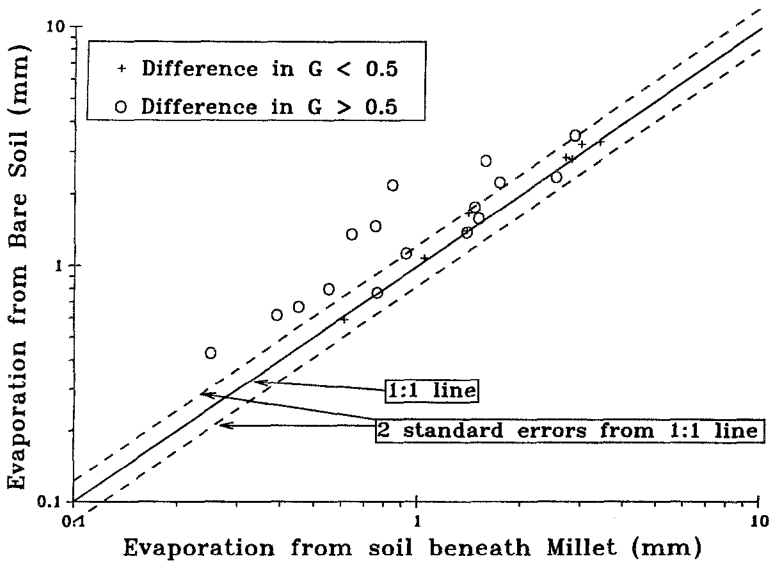

Fig. 4. A comparison of evaporation from soil measured in the Millet and Bare Soil treatments, 1993, excluding data for Day 204 (see text). Symbols and lines are as used in Fig. 3.

Table 1
Seasonal totals of measured evaporation from soil

Year/treatment	Length of period in which measurements were taken (days)	Number of days of measurement	Total measured evaporation (mm)
1991 Traditional	70	29	34.41
1991 Improved	70	29	30.37
1993 Bare Soil	59	25	42.79
1993 Millet	59	25	35.87

Table 2
Average evaporation from bare and cropped soil for 24 measurement days in 1993. Details of soil, crop and weather conditions for each evaporation period are given, an explanation of how they are calculated is given in the text

Day of 1993 (days)	LAI, G	$\theta_b-\theta_c$ (mm)	Day after rain (days)	Preceding rain (mm)	Potential evap. (mm)	Evap. from bare soil (mm)	Evap. from crop soil (mm)	Significance of difference[a]
176	0	2	1	24	–	2.83	2.80	NS
179	0	**4**[b]	1	1	–	0.59	0.61	NS
186	0	2	3	40	5.7	1.41	1.39	NS
187	**0.06**[b]	2	1	6	4.7[c]	3.33[c]	3.39[c]	NS
189	0.1	**2**[b]	1	11	6.4	3.26	2.99	NS
191	0.2	2	1	56	1.7[c]	1.67[c]	1.40[c]	NS
193	0.3	2	3	56	6.0	1.08	1.04	NS
195	0.4	**4**	1	11	4.2	2.87	2.69	NS
196	**0.5**[b]	5	2	11	4.7	1.39	1.39	NS
200	0.9	9	1	11	5.2	3.55	2.86	*
203	1.4	**11**	1	24	3.8	2.38	2.53	NS
204	1.6	12	2	24	2.7[c]	0.58[c]	0.97[c]	***
207	2.1	15	4	24	5.0	0.80	0.55	**
208	**2.30**	16	5	24	4.8	0.67	0.45	***
209	2.3	**17**	6	24	3.1	0.43	0.25	***
215	2.6	24	1	2	4.5	1.13	0.92	*
217	2.6	**25**	1	22	1.5[c]	1.47[c]	0.75[c]	***
218	**2.66**	25	2	22	4.1	2.26	1.73	*
221	2.5	25	2	16	4.3	1.59	1.50	NS
224	2.3	**25**	5	16	3.8	0.62	0.39	***
228	2.0	11	3	46	3.7	0.77	0.76	NS
230	**1.84**	**5**	1	30	1.7	2.20	0.84	***
231	1.8	4	1	7	1.3[c]	1.36[c]	0.64[c]	***
235	1.8	**2**	2	44	3.7	2.78	1.57	***

[a]Significance: NS, not significant; *, significant at 5% level; ** significant at 1% level; *** significant at 0.1% level.
[b]Day on (or nearest to) day of measurement in bold, other days are estimated by linear interpolation.
[c]Period over which evaporation from soil was measured was less than 1 day.

ration was only measured during the middle of the day (10:00–15:30 h) and is likely to be unrepresentative of E_s over the whole day. A greater proportion of daily E_s from a cropped plot is likely to occur around mid-day when the sun is overhead, than from a bare plot in which there is no shading by a canopy, hence the greater value for E_s.

4. Discussion

Fig. 2 shows that green leaf area index did not reach 1.0 in 1991 in contrast with 1993 when the highest leaf area index was 2.66. The plant density in 1993 was three times higher than the improved crop in 1991 and at least three times higher than the local farmers' millet crops. Thus, the data in 1993 should clearly show the potential influence of a crop on E_s.

The total measured evaporation from soil was reduced in the more intensely-cropped treatments by 12% and 16% in 1991 and 1993 respectively (Table 1). Although E_s was only measured on about half of the days in the measurement period in either year, the measurement days included a representative selection of 'wet' and 'dry' days. These percentage figures will therefore give an indication of the potential for seasonal reduction in E_s caused by high intensity cropping. In Niger, the seasonal E_s is estimated to account for 40% of seasonal rainfall (Wallace, 1991) and drainage represents a significant water loss in these soils (Klaij and Vachaud, 1992): hence a 16% reduction in E_s is not likely to contribute greatly to improved transpiration and crop productivity.

In a dry mediterranean environment (Western Australia), Yunusa et al. (1993b) concluded that sparse canopies of spring wheat had little direct effect on evaporation from soil. They reported only a few light rainfalls after 50 days from sowing. Similarly in northern Syria, Allen (1990) estimated that application of fertilizer resulted in a seasonal reduction in E_s of about 8% of total evaporation (E_s + transpiration). Western Australia, Northern Syria and Southern Niger could all be described as semi-arid environments. However, the cropping season of the first two environments begins in a cool wet winter and ends in a dry hot summer while the cropping season in Niger begins in a dry hot season and continues to the end of a wet hot season. In spite of these differences in climate, the effect of a crop on evaporation from the soil was observed to be small and sometimes insignificant. However, it should be noted that a small reduction in E_s achieved through crop management (although difficult to measure) could result in a significant enhancement of transpiration (T) where T is only a small fraction of rainfall and drainage is negligible (e.g. Pilbeam et al., 1995, found $T \approx 0.2$*rainfall, here a hypothetical reduction of seasonal E_s from 0.8*rainfall to 0.75*rainfall could result in $T = 0.25$*rainfall, a 25% increase in transpired water).

The insensitivity of E_s to crop management (e.g. density of cropping and application of fertilizer) and even the presence of a crop, appears to contradict the model of Ritchie (1972) especially in Niger where rainfall is frequent throughout the season and reductions to E_s due to canopy shading would be expected. In these environments this insensitivity suggests that improved management systems are not likely to affect E_s greatly. Also, the insensitivity makes accurate characterisation of the processes governing E_s difficult.

Although the reductions in total evaporation from soil were not large, the days for which there were significant differences in E_s give information about the processes influencing E_s. Differences in E_s between the two treatments were often significant from Day 185 to Day

213 in 1991 and from Day 207 to Day 235 in 1993. These periods correspond closely to the periods when there was a difference in green leaf area between the treatments. Also, significant differences in E_s were observed on days when E_s was high ($> =2$ mm) and when it was low (<0.8 mm) during these periods (Figs. 3 and 4). The most statistically significant differences in E_s occurred at rates of evaporation of about 1 mm day^{-1} or less (Figs. 3 and 4). Such rates of evaporation would be expected to occur during Ritchie's second stage, in which there is supposed to be no difference between E_s from cropped and bare soil.

In 1993, E_s measured for the first whole day after a large rain (>10 mm) was 68% or less of potential evaporation E_p (Table 2, Days 189, 195, 200, 203), except on Day 230 when E_p was only 1.7 mm. This suggests that a first stage of evaporation does not last for more than several hours after rain on this soil during days with large evaporative demand ($E_p > 3$ mm day^{-1}). In support of this conclusion, the ratio (E_s crop) / (E_s bare soil) during the first day after rain was greater than and not equal to the value of $\exp(-0.41L)$ predicted by Eq. 1 (Table 2, Days 195, 200, 203, 217).

If it is assumed that the first stage of evaporation lasts for 1 day or less, the significant reductions in E_s recorded on Days 207, 208, 209, 218, and 224 in the cropped plot, must have occurred during a second stage of evaporation (Table 2). Significant reductions in E_s during the second stage were also noted in the 1991 season. These reductions contradict Ritchie's hypothesis about the second stage which were discussed earlier. Root uptake of water, which causes differences in profile water content between bare and cropped soil ($\theta_b - \theta_c$) will have contributed to this reduction. Shading of the soil surface by the canopy may also contribute during this second stage, especially early in the stage (e.g. Day 235, Table 2).

The above discussion identifies aspects of the simple E_s models of Ritchie (1972) and Cooper et al. (1983) that do not accord with the measurements. To examine how well the models estimate daily and cumulative evaporation from an initially wet soil profile, outputs from the two models are compared with 1993 field data in Fig. 5. The field data presented are average daily E_s values during a period when the crop was well established (i.e. Days 200, 203, 207, 208, 209, 218, 221, 224, 228, 230, 235, Table 2). Because average E_s values are used the estimates of E_s from the models were determined assuming (1) a constant average value of potential evaporation, $E_p = 3.9$ mm day^{-1} (calculated from all days of field data) and (2) a leaf area index (L) and green leaf area index (G) of 2.0. The original description of the model by Ritchie (1972) was followed as closely as possible. Bley et al. (1990) estimated values of parameters in the Ritchie model ($U = 3.0$ mm; $\alpha = 2.1$ mm day$^{-1/2}$) from field measurements made at the ICRISAT Sahelian Center. These values were supported by measurements of E_s from bare soil in 1991 (Daamen, 1993).

Clearly, the application of Ritchie's two-stage model does not provide a good description of the effect of a crop on E_s. First stage evaporation apparently persisted for 2 days beneath the crop and only a little more than 1 day on bare soil. An unrealistically large E_s value on the third day after rain (the first whole day of second stage drying) was noted beneath the crop. This may have been the result of a inadequate estimates of U and α. However, daily E_s from beneath a crop was larger than that for bare soil and always would be so during the second stage of evaporation in Ritchie's model.

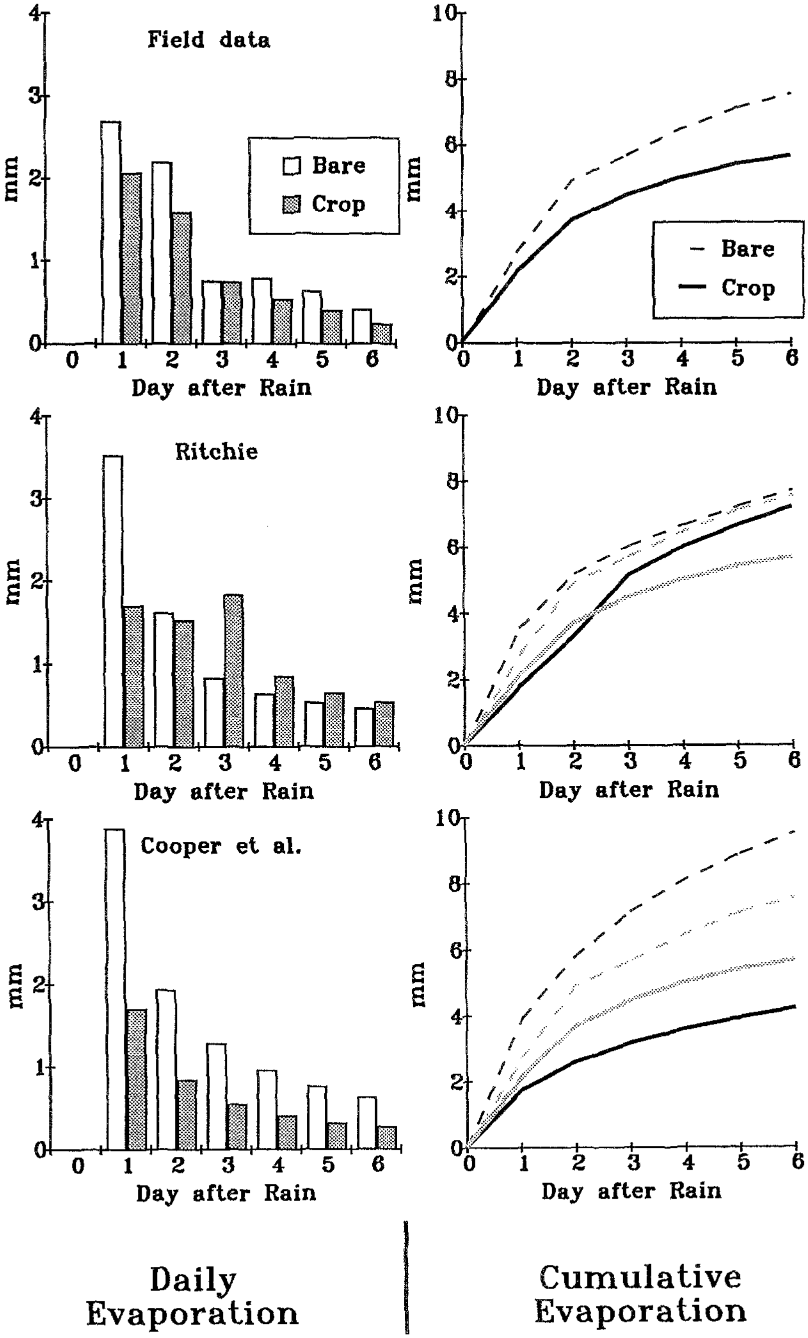

Fig. 5. Daily and cumulative evaporation from bare soil and from soil beneath a crop following an initial wet condition. Field data from Niger in 1993 and estimates of two models (Ritchie, 1972; Cooper et al., 1983) are presented. Cumulative evaporation measured in the field is plotted as lighter lines on the plots with results from the models.

The model of Cooper et al. (1983) greatly exaggerated the effect of the crop on E_s on all days after rain. Allen (1990) also noted that this model overestimated the reduction in E_s in cropped soil. Cooper et al. consider that the reduction in radiant energy at the soil surface beneath a crop (soil shading) causes a proportional reduction in E_s at all times after rain, giving this large reduction (Fig. 5). (The two-stage model assumes that such a reduction in daily E_s only occurs during first stage.)

In reality, both root water uptake and soil shading can contribute to a reduction of evaporation from soil beneath a crop, but they act in different ways. Shading of the soil by a crop canopy effectively reduces evaporative demand, and root water uptake reduces soil profile moisture (thus hydraulic conductivity) thereby restricting water movement to the soil surface. For the environment in Niger we postulate below that root water uptake is the dominant cause of reduced E_s from cropped soil. Exceptions occurred when evaporative demand was low immediately following rain (e.g. Days 230 and 231, Table 2), in which case soil shading was the more likely cause of reduced E_s.

4.1. The effect of root water uptake on E_s

If root water uptake is causing a reduction in E_s then this would be the result of lower soil water content in the cropped plots. Indeed, throughout most of the period of significant differences in E_s during the 1993 season, there was a difference in soil profile water content (5–90 cm) between the cropped and bare plots (Table 2). Although evaporation from soil is primarily influenced by soil water contents near the surface (for example 0–10 cm), these measurements were not made. Differences in soil water content from 5–90 cm should provide a good indication of whether root water uptake is likely to have caused differences between cropped and bare plots.

The effect of root water uptake is likely to be largest when differences in green leaf area (i.e. transpiring leaf area) are largest, whereas soil shading is a function of total leaf area irrespective of transpiration. In 1991, significant differences in E_s were observed until Day 213, but not thereafter. The green leaf area of the two treatments became similar at about this time. However, the improved crop was not harvested until Day 243, and therefore the total leaf area of the improved crop would have been higher than green leaf area between Day 220 and 243, although leaf senescence was occurring. Greater shading of the soil surface by the improved crop during this period appeared to have little influence on E_s.

A study on an alfisol in semi-arid India recorded little difference in E_s measured on a bare soil and a bare soil shaded with shade screens (Daamen, 1993). It was concluded that when evaporative demand can not be met by E_s throughout the first day after rain, shading of the soil surface will not effectively reduce E_s. In Niger, the evaporative demand is often not met throughout the first day after rain (see Table 2; note also that $U=3$ is less than most daily E_p values). This supports our hypothesis of root water uptake as the dominant cause of E_s reduction. Both Allen (1990) and Yunusa et al. (1993b) recognised root water uptake as an important process influencing E_s.

4.2. Towards an improved model of E_s beneath a crop

Further consideration of processes discussed in the development of the two-stage model of Ritchie (1972) suggests some simple additions which can be made to improve the way it accounts for the presence of a crop. The predictions of the Ritchie model differed from field data in two main ways. First, differences in E_s between bare soil and crop are too large on the first day after rain. Second, the model overestimates evaporation from the soil surface of the cropped plot throughout the second stage of evaporation. The causes of these two errors in prediction of E_s are discussed below.

The use of Eq. 1 relies on the assumption that E_s is directly proportional to incident solar radiation (i.e. the aerodynamic term in Eq. 4 is assumed to be insignificant). At field sites where meteorological measurements have been made, this assumption is easily checked. It was not found to be accurate at our field site in Niger or by Yunusa et al. (1993b), who reported that the aerodynamic term was twice as large as the radiation term in Eq. 4 for more than half of the season in Western Australia (Despite this, Yunusa et al., 1993b and Yunusa et al., 1993c, continued to use Ritchie's model successfully, perhaps because rainfall events were rare).

If meteorological conditions can only be estimated, or an average seasonal effect is to be modelled then the following approach to accounting for the evaporation due to the aerodynamic term can be used. Assume that the magnitude of the aerodynamic term is a fixed proportion, W, of the radiation term. In cases where Ritchie's assumption is valid (e.g. temperate humid climates), $W \approx 0.0$; for the study of Yunusa et al. (1993b) (a hot dry climate), $W = 2.0$, for most of the season. This approach to accounting for the aerodynamic term was discussed by Priestley and Taylor (1972) and Jury and Tanner (1975) for well-watered surfaces. If we also assume that the aerodynamic term is not affected by the presence of a sparse crop, Eq. 6 can be derived and then used in place of Eq. 1 (taking T_R = the radiation term, Eq. 4 can be written as $E_p = T_R(1+W)$ and $E_{pc} = T_R\exp(-KL) + T_R W$ and elimination of T_R leads to Eq. 6):

$$E_{pc} = E_p\left(\frac{\exp(-KL) + W}{1+W}\right)$$

This treatment effectively reduces the large differences between E_s from a bare soil and beneath a crop on the first day after rain, and it is consistent with current knowledge of evaporation processes.

The second problem with the application of the Ritchie two-stage model was that during second stage evaporation, it was predicting higher E_s from beneath the crop than on the bare soil while measurements showed the reverse to be true. A likely explanation is that the model made no allowance for root uptake of water from the soil.

To take account of root uptake of water, a simple conceptual model of water balance near the soil surface is used, based on the following assumptions which are consistent with earlier work (Daamen et al., 1993). Consider that E_s is the evaporative water loss from a shallow near-surface layer, for example the top 100 mm of soil. The other water losses from this layer are drainage and root water uptake. No significant upward movement of water occurs at 100 mm given that the soil has a high sand fraction and that rain events are reasonably frequent during the rainy season. Drainage at 100 mm is only significant for one or two days after heavy rain and this period coincides with the first stage of evaporation. Also, drainage at 100 mm following a large rain event will occur in both bare and cropped soil profiles, but root water uptake will occur only in cropped profiles. The initial root water uptake does not cause a difference in water content between a bare and a cropped plot because the lack of root water uptake will be compensated for by faster drainage and evaporation in the bare soil profile. However, when drainage ceases, differences will begin to emerge. Using this reasoning, root water uptake is only likely to effect a change in the near-surface water content during second stage evaporation.

Many factors influence root water uptake (e.g. leaf area index, root density distribution, and the distribution of soil water) and obviously a simple model will have to make approximations. Here, the case of a sparse millet crop ($G=2$) in Niger is considered. As the 0–100 mm layer dries, both evaporation from the surface and root water uptake from the layer will decrease. These two losses of water are likely to be well correlated because both depend on the matric potential within the layer. As a first approximation, it is assumed that these two losses are proportional throughout second stage evaporation, with a proportionality constant, V. This leads to the following approach to modelling evaporation during the second stage. A bare soil profile has only one loss of water, $E_{s,2}$, whereas a cropped profile has effectively $(1+V)E_{s,2}$ from the surface layer, and hence dries more quickly. The concept that the evaporation rate is inversely proportional to the cumulative loss of water is applied. At the end of each day, cumulative loss from a cropped profile (i.e. the sum of evaporation from soil and root water uptake $\Sigma(1+V)E_{s,2}$) is used to define the "equivalent time into second stage for a bare soil" (denoted $t_{2,eq}$ in Eq. 7):

$$t_{2,eq}=\left(\frac{\Sigma(1+V)E_{s,2}}{\alpha}\right)^2 \qquad (7)$$

Evaporation from soil for the following day is then calculated as:

$$E_{s,2}=\alpha\sqrt{t_{2,eq}+1}-\alpha\sqrt{t_{2,eq}} \qquad (8)$$

Using these corrections to form a new model, the simulated E_s data resembled the observed data much more closely (Fig. 6). In addition to the values of U and α already defined, W was set equal to 0.5 after inspection of the meteorological data. V was set equal to 1.0, which is reasonable given that the green leaf area was 2 and that the millet root density is

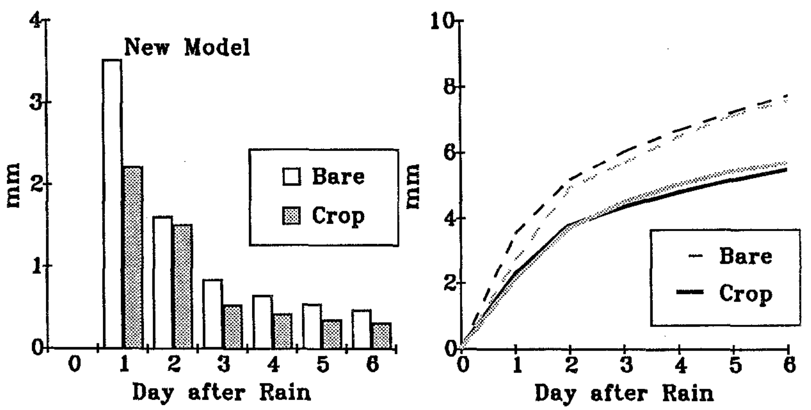

Fig. 6. Estimates of daily and cumulative evaporation from bare soil and from soil beneath a crop using a new model described in the text. Cumulative evaporation measured in the field (from Fig. 5) is plotted as lighter lines on the cumulative evaporation plot.

at a maximum near the soil surface (Payne et al., 1990; S.R. Gaze, personal communication, 1993). First stage evaporation was assumed to have the same duration beneath a crop as it has on bare soil, using the reasoning (given above) that the water content of the near surface layer follows the same course during the first stage in both bare and cropped soils. The duration of first stage drying was calculated using U and values of E_p estimated using Eq. 4.

The implementation of the model used here is well suited to a sandy soil in an environment with high evaporative demand. It has not yet been applied to other soils and environments. However, the approach used suggests that a crop is likely to be most effective in the reduction of E_s in temperate humid regions (i.e. in conditions where $W \approx 0$) and under crops with high leaf areas (i.e. high $V > 1$). Crops that extract water from the soil near the surface, effectively competing with E_s for soil water, will achieve a greater reduction of E_s. The environments of the studies of Yunusa et al. (1993b), Allen (1990), and this study are characterised by high W and low V values and consequently showed little reduction in E_s with the presence of a crop. Irrigated areas of dry regions usually experience large advection and thus have higher values of W (Jury and Tanner, 1975) and a lower potential for reduction of E_s.

Some factors will need further consideration before this modification of the two-stage model can be implemented more widely. For example, the influence of potential evaporation during second stage drying, the effect of short first stages of drying (< 1 day), and indeed the need for two separate stages of drying must be carefully considered. Also, it should be noted that W and V are by nature variable. However, the constant positive values used here ($W = 0.5$, $V = 1.0$) provide a considerable improvement in the estimation of E_s beneath a crop when compared with the approach used by Ritchie (1972) (which effectively used values of $W = 0$, $V = 0$). Our approach is useful at sites where few measurements are made or in areas where conditions must be estimated. Furthermore it does not rely on any additional theoretical development, it simply applies the approach in a new way.

Acknowledgements

The authors would like to thank the Natural Resources Institute of the UK Overseas Development Administration for their financial support (EMC X0134). They are also grateful to members of staff at the ICRISAT Sahelian Center, Niamey, for their contributions to this work. This paper was approved for publication as Journal Article JA 1535 of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

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