Effect of varying evaporative demand on the relationship between actual and potential evapotranspiration at different soil moisture deficits in potato (*Solanum tuberosum*) crops

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Summary

A series of close relationships were established in four cultivars of potatoes between the ratio of actual (AE) : potential (PE) evapotranspiration (ET) and soil moisture deficit (SMD) for different daily ET rates from experiments conducted on sandy loam soils at Cambridge University Farm over the period 1989-93. These showed that there was a limiting SMD at which the ratio of AE : PE decreased rapidly with increasing SMD and this limiting SMD was inversely related to daily ET rate. However, even at small SMDs, as daily ET rate increased there was a significant, slow decrease in AE : PE ratio. In order to maintain potential ET rates in conditions of high and extreme demand in the UK (e.g. 5-7 mm/day), crops need to be maintained at < 25 mm SMD but allowable SMDs can be increased as demand moderates. Irrigation scheduling needs to take account of these findings in order to avoid under- or over-irrigating crops when ET demand is high.

Key words: Potato, evapotranspiration, soil moisture deficit, irrigation scheduling

Introduction

Water is extracted from the soil by roots and their depth and distribution are key factors influencing the accessibility of water, its use to satisfy the demand created on the canopy by the atmosphere and hence yields. Gregory & Simmonds (1992) stated that the apparent drought sensitivity of potatoes may be caused by the limited ability of the root system to convey water. They speculated that the low values for below ground conductance of water in the plant were due primarily to the relatively small total root length per unit area of soil rather than an inherently small conductance per unit length of root. However, Stalham & Allen (2001) showed that, in the absence of compaction, total root length in irrigated potatoes was typically 14-15 km/m^2 of soil surface area, which compared favourably with, or exceeded, other spring sown crops including sugar beet. For a given soil type, the rate of AE depends on the both the SMD and the rate of PE demand on the canopy (Denmead & Shaw, 1962; Bailey & Spackman, 1996). When ET rates are high, plants lose turgor faster and stomatal closure occurs earlier at lower SMDs than when ET rates are low. Therefore, for scheduling purposes, it is important to identify the limiting SMD (defined as the point at which the AE : PE ratio drops below 1.0) for different daily ET demands. However, when the rooting system is poorly developed early in the crop's life, a smaller SMD may cause daily AE to fall below PE, whereas later in the season when the rooting system is more developed it may be able to withstand a greater SMD and still function at the PE rate, or sustain high daily water use under conditions of extreme ET demand.

A series of seven experiments on potatoes were conducted on stony, sandy loam soils (Milton Series, Anon, 1983) at Cambridge University Farm (CUF) over the period 1989-93 to establish the relationship between AE : PE ratio and SMD for different daily ET rates.

Materials and Methods

General

In order to exclude rainfall, most experiments were grown under large permanent polythene rainshelters (16 × 8 m, Polybuild Ltd). Temperatures were increased under the rainshelters compared with ambient but the cladding polythene ended 30-50 cm above the ground at the sides of the shelter and the ends had large openings so air flow through the shelters was good and crops performed similarly to those grown outside the shelters. Two experiments were subjected to natural rainfall (Expts 3 and 5; Table 1). Seed tubers (25-35 mm) were planted 9-11 cm deep into pre-formed rows 71 or 76 cm wide at a spacing of 20-25 cm using hand dibbers. Plot size was either two or three harvest rows, bordered by a guard row on either side, and 5 m in length. Planting dates ranged from 23 March to 7 May.

Table 1. *List of experiments, varieties, irrigation treatments and amounts applied*

Expt	Year	Variety	Irrigation regimes	Total irrigation applied (mm)
1	1989	Record	None (Dry); irrigated at 20 mm SMD 16-44 DAE, then at 40 mm SMD (Moist); irrigated at 10 mm SMD (Wet)	Dry, 0; Moist, 347; Wet, 453
2	1990	Cara	None (Dry-Dry); irrigation starting 44 DAE whenever limiting SMD* reached (Dry-Wet); SMD maintained < 20 mm from planting to 44 DAE (Wet-Dry)	Dry, 0; Dry-Wet, 187; Wet-Dry, 101
3	1990	Cara; Desiree	Unirrigated; Irrigated (CUF†)	Unirrigated, 0; Irrigated, 202
4	1991	Cara; Estima; Record	None (Dry); Irrigated (CUF)	Dry, 0 Estima, CUF, 209; Record, CUF, 259; Cara, CUF, 306;
5	1991	Cara; Desiree	Unirrigated; Irrigated (CUF)	Unirrigated, 0; Irrigated, 197
6	1992	Cara	No irrigation (W1); dry until 44 DAE, then irrigated at same frequency as W6 (W2); irrigated as W6 from 21-72 DAE (W3); irrigated as W6 from emergence until 72 DAE (W4); irrigated according to CUF (W5); irrigated to maintain SMD at 10-25 mm (W6)	W1, 0; W2, 187; W3, 229; W4, 144; W5, 313; W6, 354
7	1993	Cara; Estima	No irrigation (Dry); irrigated according to CUF (CUF); irrigated to maintain < 25 mm SMD (Wet)	Dry, 0; Cara, CUF, 335; Cara, Wet, 378; Estima, CUF, 216; Estima, Wet, 265

*The limiting SMD for scheduling was defined as the amount of water available within the rooting zone held at a tension of less than 60 kPa, ranging from 20-45 mm depending on rooting depth.
†CUF = Cambridge University Farm Potato Irrigation Scheduling Scheme; irrigation applied when limiting SMD reached.

The experimental design in Expts 1, 2, 4, 6 and 7 was a randomized block, with the treatments being all combinations of variety and irrigation regime as shown in Table 1. Experiments 3 and 5 were randomized split-plot designs with irrigation treatments as main plots and varieties allocated to sub-plots. There were four replicates in Expts 1, 2, 3 and 5, whilst the remaining experiments had three. Variates were analysed by analysis of variance using the Genstat 5 statistical package (Payne *et al.*, 1993). Treatment means were judged to be significantly different only if the probability of differences occurring by chance was less than 5 % ($P < 0.05$).

Irrigation

Irrigation treatments were scheduled using the CUF irrigation scheduling model based on a modified Penman-Monteith ET equation. Reference crop ET (ET_0) was calculated using the parameters of Allen *et al*. (1998) for a grass reference crop. The potato irrigation model takes account of changing leaf area index, stomatal conductance and canopy surface roughness on the demand side and root growth and limiting SMD based on soil water tension and rooting depth on the supply side. Meteorological data were collected using an electronic logger (Delta-T Devices Ltd or Schlumberger) attached to an anemometer (Vector Instruments), a screened, combined relative humidity sensor and air temperature thermistor (Skye Instruments Ltd) and a pyranometer measuring total incident global radiation (Kipp & Zonen BV) all located at 2 m height on a mast situated within the experimental field. Sensors were duplicated inside the rainshelters so that ET_0 could be calculated for the covered crops.

In Expts 1, 2, 4, 6 and 7, drip irrigation was applied with 17 mm diameter solid wall, pressure-compensated dripper lines, with drippers at 30 cm spacing discharging 1.6 l/hour at 2 bar pressure (Ram 17, Netafim). A single dripper line per row was used, off-set 10 cm from the centre of the row to prevent water dripping down the outside of neutron probe (NP) access tubes. Irrigation amounts were calculated based on flow meter readings and the spacing of the drippers. Overhead irrigation Expts 3 and 5 was applied through a boom (RST Irrigation) and hose reel (Perrot SA, SH63/280) combination. Mean irrigation amounts were estimated from multiple raingauges per irrigation treatment, situated at ground level and not shielded by foliage.

Neutron probe measurements

A Soil Moisture Probe Type IH II (Didcot Instrument Co. Ltd) was used to measure the changes in soil water content. Aluminium access tubes of 45 mm external diameter were pushed into 40 mm diameter holes made using a gouge corer (Eijkelkamp) attached to a percussion hammer (Atlas Copco), until the top of the tube was between 10 and 20 cm above the soil surface. The access tubes were installed at crop emergence mid-way between two plants in the centre of the row approximately 1 m in from the end of the plot, with a single tube per plot. For the data presented in this paper, measurements were taken immediately prior to irrigation events and at the same time of day whenever possible. In most experiments, measurements of soil water content using the NP were made at frequent intervals (1-3 days) during which irrigation was not applied to avoid confounding the measurement of soil water with large amounts of water entering the soil (see Gaze *et al.,* 2002).

Results

In view of the restricted length of this paper, the presentation of the results focuses on Expt 7 but the same analyses were performed on the other experiments detailed in Table 1 with similar results. The water use (AE) of the crop was calculated for the 1-3-day periods and compared with PE.

Potential ET was estimated from K_c*ET_0, where K_c is a function of ground cover, crop height and stomatal conductance. Initially, only crops with full ground cover were compared but this eliminated some useful data when the canopy was expanding and subjected to high atmospheric evaporative demand, so subsequently all the short measurement periods of soil water content were included in the analysis. These periods started at *c*. 40 % ground cover in most experiments which eliminated the first 3-4 weeks after emergence. The ratio AE : PE was plotted against the SMD at the start of the measurement period rather than the mean SMD for the period (Fig. 1). The ratio of AE : PE was relatively unaffected by increasing SMD up to *c*. 40 mm (remaining close to 1.0) but then decreased with further increase in the SMD at the start of the measurement period. During the phase when the AE : PE ratio was decreasing, the reduction in AE was greater for Estima than Cara and suggested a cessation of transpiration at a lower SMD (80 *cf*. 100 mm).

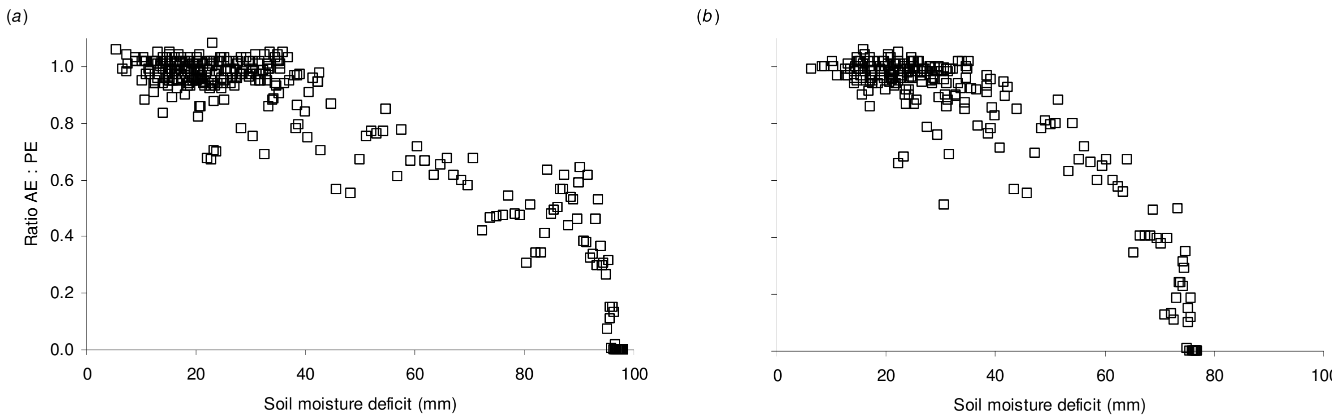

Fig. 1. Relationship between the ratio of actual (AE) : potential (PE) evapotranspiration and soil moisture deficit in (*a*) Cara and (*b*) Estima in Expt 7.

Figure 2 shows the AE : PE ratio in Expt 7 during the 1-3 day measurement periods in relation to the average daily ET_0 and SMD during each period. In the Dry Cara plots, as the soil water reserves were depleted, AE : PE dropped gradually during May. On 7-8 June, ET_0 increased dramatically to an average of 5.65 mm/day resulting in a drop in AE : PE from 0.74 to 0.56 (Fig. 2*a*). However, over the following three days ET_0 decreased to 3.05 mm/day and the AE : PE ratio increased back to 0.71. There was a similar, but longer, period of high ET_0 in early-July (average 4.76 mm/day for a 7-day period) which steadily reduced the AE : PE ratio. However, as earlier, the subsequent decrease in ET_0 demand over the next 7 days (2.63 mm/day) resulted in a significant recovery in AE : PE ratio. Clearly, even when plants were under severe water stress (the SMD at the beginning of July was 78 mm), a significant decrease in the evaporative demand allowed their root systems to access sufficient water in the soil to meet the greater proportion of the reduced demand. Similar, temporary, alterations in AE : PE ratio occurred in both irrigated treatments during late June and early July when ET_0 averaged 4.5 mm for a 2 week period followed by a cooler period when ET_0 decreased and AE : PE ratio recovered (Fig. 2*b*; *c*). The data for Estima (not shown) were similar in terms of response of AE : PE ratio to fluctuating ET_0 demand.

The effect of varying ET demand on the canopy on AE : PE ratio was further analysed by plotting the AE : PE ratio against SMD for different reference crop ET_0: 1-2, 2-3, 3-4, 4-5, 5-6 and 6-7 mm. It was felt that using reference crop ET_0 rather than the potato crop ET would permit comparison between crops with partial ground cover and those with full ground cover. Using a split-line approach, linear regressions were fitted to the data using the Penman (1970) principle of an abrupt change in the ratio of AE : PE equating to the limiting SMD. In these results, this was the split point for two lines of statistically different slope. Individual analyses were conducted in Genstat for each variety in each experiment and for all ET_0 values close relationships were found which allowed the limiting SMD to be established and the slopes of the lines either side of the limiting SMD (Table 2). The established relationships were close-fitting as demonstrated by the R^2 values in Table 2. Figure 3 presents the data from Table 2 in a visual form that is easier to interpret but for Cara only to avoid excessive duplication of data.

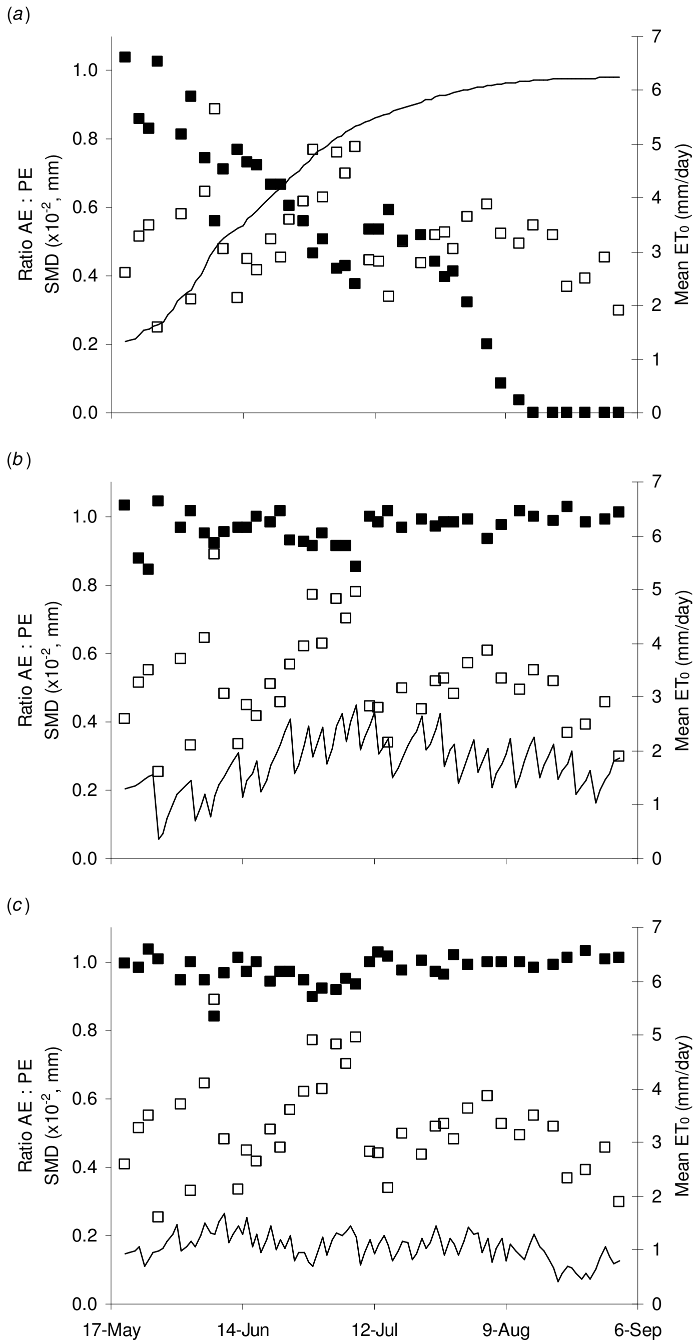

Fig. 2. Ratio of actual (AE) : potential (PE) evapotranspiration, mean ET_0 during the measurement period and soil moisture deficit (SMD) in Cara in Expt 7. (*a*) Dry; (*b*) CUF; (*c*) Wet. AE : PE ratio (■); ET_0 (□); SMD (—).

Table 2. *Limiting soil moisture deficit (SMD) and slope of linear regressions between AE : PE and SMD before and after limiting SMD in (a) Cara and (b) Estima in Expt 7*

ET_0 (mm/day)	Limiting SMD	S.E.*	Slope before limit	S.E.*	R^2	Slope after limit	S.E.*	R^2
(a)								
1-2	62.6	2.86	-0.0017	0.00013	0.83	-0.0222	0.00111	0.91
2-3	49.4	2.19	-0.0011	0.00007	0.87	-0.0197	0.00081	0.94
3-4	42.2	2.13	-0.0017	0.00010	0.89	-0.0168	0.00067	0.96
4-5	34.0	1.74	-0.0020	0.00013	0.84	-0.0150	0.00074	0.89
5-6	27.9	1.67	-0.0055	0.00028	0.91	-0.0121	0.00053	0.93
6-7	25.5	1.49	-	-	-	-0.0097	0.00040	0.96
(b)								
1-2	59.2	2.90	-0.0015	0.00010	0.82	-0.0294	0.00121	0.94
2-3	45.6	2.21	-0.0015	0.00009	0.84	-0.0286	0.00120	0.97
3-4	36.6	1.85	-0.0038	0.00022	0.85	-0.0230	0.00099	0.97
4-5	34.4	1.92	-0.0061	0.00033	0.88	-0.0203	0.00084	0.94
5-6	26.4	1.49	-0.0081	0.00045	0.87	-0.0170	0.00090	0.90
6-7	23.7	1.40	-	-	-	-0.0168	0.00071	0.95

*S.E.s have variable (8-10) degrees of freedom

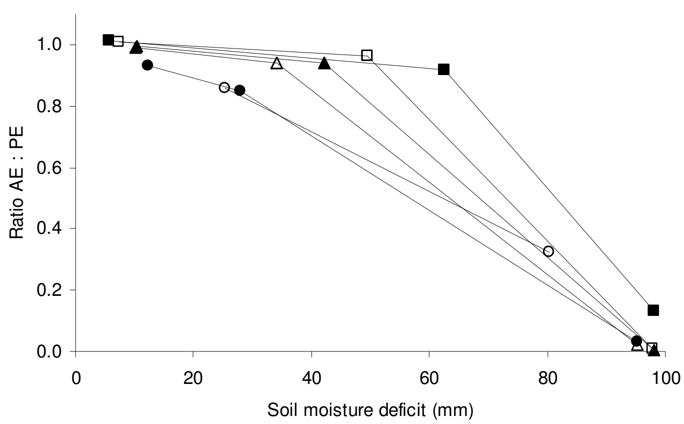

Fig. 3. Relationship between ratio of actual (AE) : potential (PE) evapotranspiration and soil moisture deficit for varying daily ET_0 in Cara in Expt 7. ET_0 (mm): 1-2 (■); 2-3 (□); 3-4 (▲); 4-5 (Δ); 5-6 (●); 6-7 (○).

The results show a number of important features. First, the AE : PE ratio was close to 1.0 when the SMD was close to field capacity or zero SMD (Fig. 3). Secondly, there was a sudden change in the slopes of the lines which indicated the limiting SMD. This limiting SMD decreased as the daily ET_0 demand increased and was slightly lower for Estima than for Cara, but not significantly so (Table 2). Thirdly, prior to the noticeable change in the relationship between AE : PE and SMD at the limiting SMD, the AE : PE ratio was decreasing as the soil became drier even at low SMDs, and became more steeply negative as ET_0 increased. This differs from the approach of Penman (1970) and French & Legg (1979) who surmised that crops functioned at potential (i.e. AE = PE) until the limiting SMD was reached. Clearly, the results from the current study differ from this conclusion. Fourthly, the rate of decrease in AE : PE as SMD increased beyond the limiting SMD was steeper at low ET_0 than at high ET_0, and all lines converged to a point (96-98 mm in Cara and 76-79 mm in Estima) where the AE : PE ratio was zero. When combining data from Cara and Estima over Expts 4 & 7, the same type of close relationships were found but as a result of only small variation in texture and stone content between experimental fields, limiting SMDs were similar. Using data from all experiments detailed in Table 1, other varieties also showed similar close relationships (Table 3).

Table 3. *Effect of daily ET_0 rate on limiting SMD in different varieties combined over experiments*

		ET_0 range (mm/day)					
Variety	Expt	1-2	2-3	3-4	4-5	5-6	6-7
Cara	2-7	55.4	49.7	35.6	27.8	24.0	20.7
Desiree	3, 5	54.2	47.8	42.1	34.6	24.7	19.0
Estima	4, 7	60.2	45.3	37.3	33.5	26.0	21.4
Record	1, 4	61.7	51.1	44.5	38.0	24.3	19.2

Discussion

In drying soils, large suction gradients develop between the root and the soil around it. Water movement through the plant arises from a gradient in diffusion pressure deficit between the transpiring leaves and the roots. This deficit can be assumed to be proportional to the actual evapotranspiration rate, AE. Therefore, in order to maintain AE in a drying soil where the capillary conductivity is decreasing and the suction at the plant roots is increasing correspondingly, the diffusion pressure deficit in the leaves must continually rise so that the necessary deficit gradient between leaf and root is maintained. The rise in diffusion pressure deficit in the leaves is accompanied by a decrease in turgor pressure resulting in stomatal closure, dehydration of the leaves and wilting. Consequently, the permeability of the plant to water flow decreases and AE slows. Similarly, higher daily ET_0 rates will increase the rate of increase in the diffusion pressure deficit of the leaves leading to a more rapid fall in turgor and the permeability of the plant with decreasing soil moisture supply. Thus, it would be expected that AE rates would decrease with increasing SMD and this decrease would be more rapid as PE rates increase. The results fully support these hypotheses. The SMD at which the decrease in AE : PE ratio commences depends on both soil and root properties. In sandy soils, where most of the water is held at low tension, the decrease in AE : PE ratio should not be evident until most of the available water has been depleted and there will be an abrupt drop in AE : PE ratio. In soils in which tension increases rapidly as SMD increases, the decrease in AE : PE ratio should be noticeable at comparatively low SMDs but will drop only slowly as SMD increases. Penman (1970) suggested that unrestricted crop growth (i.e. AE = PE) continued until soil water content was depleted and the limiting SMD was reached. As the soil dries beyond the limiting SMD further water loss and growth are deemed to cease. Penman acknowledged that this was too drastic a division but was simple and seemed to work. The results in the current experiments, however, indicated that the AE : PE ratio was decreasing before the limiting SMD was reached, except when ET demand was very low and as ET_0 increased the slope became more steeply negative. The current study also showed that subsequent to the limiting SMD being reached, the decrease in AE : PE was faster at low ET_0 than at high ET_0, whereas Denmead & Shaw (1962) and Bailey & Spackman (1996) had parallel lines for different ET_0. All lines converged to a point where water uptake ceased completely but this could not be defined as the critical SMD, since unirrigated Cara plants continued to survive even though they were apparently not using water according to NP measurements.

The fit of the linear regressions of AE : PE verses SMD prior to the limiting SMD was close but poorer than the fits of the lines subsequent to the limiting SMD. This was probably in part because some juvenile crops with undeveloped rooting systems were measured which would have been less capable of extracting soil water, particularly at high demand, and would affect the relationship between AE : PE ratio and SMD. However, some of these crops had incomplete canopy covers and therefore would have had a lower daily demand for water which the rooting system could have supplied more completely. Further examination of the data for all crops with incomplete canopies showed a cluster of points in unirrigated crops in Expt 1 that had lower AE : PE ratios (0.57-0.70) than expected for the SMD (18-31 mm). By comparison, the crops maintained at an SMD of 9-15 mm had AE : PE ratios over the same period of 0.89-0.96. The daily ET_0 in this 12-day period was *c*. 4.6 mm but frequent measurement of SMD began 10 days after emergence when the canopies were small (*c*. 20 % ground cover) and depth of water extraction shallow. Such extreme demand during May is rare but it does show that young plants can come under water stress even at small SMDs when the rooting system is small.

For all irrigation scheduling, it is important to recognize the importance of commencing irrigation just prior to the limiting SMD being reached so that the field can be completely irrigated before plants commence closing their stomata and begin to wilt. Further, when ET demand is extreme, growers have to irrigate to satisfy the demand on the crop canopy and reduce the SMD to a point where roots can function at a lower suction potential. In order to maintain potential evapotranspiration rates in conditions of extreme demand that occur infrequently in the UK (e.g. 5-7 mm/day), crops would need to be maintained at SMDs < 25 mm but SMDs can be increased when the demand is less extreme. Owing to the frequency of intense or prolonged rainfall events in the UK, irrigation and overall water use efficiency is improved by maintaining higher SMDs since there is a greater capacity for accommodating rainfall and preventing the drainage loss which often occurs on soils maintained at small SMDs. On the soils at CUF this would typically be *c*. 40 mm during July and August when the ET_0 averages 3.1 mm/day. Nevertheless, growers often panic when ET_0 exceeds 30 mm/week, i.e. 4.3 mm/day, since their irrigation capacity is frequently less than the 25 mm/week needed to satisfy an average potato crop ET demand after allowing for evaporation during application. Soil moisture deficits increase rapidly under such ET demand and therefore crops do not use the amount of water growers think they should when looking solely at ET_0 data. Growers who have extra irrigation capacity that more closely matches ET_0 rates often over-irrigate during such periods since their crops are incapable of using all of the water applied, particularly if there is soil compaction which restricts rooting density and therefore reduces water uptake.

Acknowledgements

The authors wish to acknowledge financial support from the Ministry of Agriculture, Fisheries and Food (now DEFRA) in the form of a studentship for postgraduate study, Cambridge University Potato Growers Research Association and more recently the British Potato Council (formerly the Potato Marketing Board). Special thanks should be extended to members of the team at CUF for their help.

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