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Water uptake in the potato (*Solanum tuberosum*) crop

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SUMMARY

Experiments were conducted on sandy loam soils at Cambridge University Farm over the period 1989–99 to examine the effects of irrigation regime and variety on water uptake (WU) in potatoes. Unirrigated crops extracted water from considerable distances ahead of the rooting front but frequently watered crops took up water from depths shallower than the current depth of rooting. There was an increase in the extraction of soil water at depth if crops were irrigated less frequently at moderate (i.e. 40 mm) soil moisture deficits (SMD). The SMD measured at different positions across the ridge always differed and the relationship changed during the season. This is of concern since most reports on water use in potatoes are based on a single measurement position for the neutron probe in the centre of the ridge and this location over-estimates crop water use. Crops grown on the flat had a more uniform extraction of soil water across the row width than crops grown in ridges but there was no evidence that having one part of the rooting system drier than another affected overall crop water use. Once rooting systems were established to considerable depth, WU continued from deeper roots even though upper horizons were periodically re-wetted by irrigation. For this reason, it proved impossible to relate WU to rooting density in specific horizons over the course of the season. Only early in the season did the proportion of total WU correspond reasonably closely with the proportion of total root length in each horizon. It appeared that the pattern and extent of soil drying created by a crop changes the horizons where water is extracted at different growth stages and the relative rooting density in a particular horizon is not a good indicator of the potential to take up water from that depth. Although rooting density decreased rapidly with increasing depth, roots deeper in the profile contributed a considerable component of total crop water requirement irrespective of the water status of horizons closer to the soil surface.

A series of close relationships were established between the ratio of actual : potential evapotranspiration and SMD for different daily evaporative rates. These showed that there was a limiting deficit at which the ratio of actual : potential evapotranspiration decreased rapidly with increasing SMD and this limiting deficit was inversely related to daily evapotranspiration rate. However, even at small SMDs, as daily evapotranspiration rate increased there was a significant, slow decrease in actual : potential evapotranspiration ratio. In order to maintain potential evapotranspiration rates in conditions of extreme demand in the UK (e.g. 5–7 mm/day), crops need to be maintained at <25 mm deficit but allowable deficits can be increased as demand moderates.

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 (TRL) rather than an inherently small conductance per unit length of root. However, Stalham & Allen (2001) showed that, in the absence of compaction, TRL in irrigated potatoes was typically 14–15 km/m², which compared favourably with, or exceeded, other spring-sown crops including sugar beet. However, the range in published maximal TRL for potatoes is large, from 1·6 to 24·1 km/m² (Stalham & Allen 2001), which may be more a consequence of soil structural conditions than the inherent inability

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of the potato plant to produce a large, dense rooting system per se, since potatoes have been shown to be sensitive to compaction (Boone *et al.* 1985; Van Oijen *et al.* 1995; Rosenfeld 1997).

Soil water extraction by plants has been described at many levels of complexity in order to calculate the rate of water uptake (WU) from soil as demanded by the atmosphere. In most models, many of which were reviewed by Molz (1981), the rate of WU depends mostly on the root length per unit volume of soil (RLD, cm/cm^3), or per unit area of soil surface (TRL, km/m^2). Sometimes a distinction has been made between 'active' and 'non-active' roots (Nimah & Hanks 1973), although which roots are functionally capable of taking up water is still poorly understood. When water supply to the roots is not limited, crops with closed canopies should transpire water at a rate corresponding closely to potential evapotranspiration (ET). If the soil water content is similar throughout a homogeneous soil profile, it could be assumed that WU will be distributed within the soil profile as some function of RLD, with the depth integral of WU equalling the actual transpiration rate. However, experimental evidence from field crops has indicated that there are environmental conditions where RLD and TRL are not well correlated with either WU or transpiration rate, such as when some parts of the deeper profile have a plentiful supply of water and short lengths of root in these layers are able to supply the crop adequately, whilst more densely rooted layers rapidly dry out (Gregory *et al.* 1978; Sharp & Davies 1985). In irrigated crops, soil water is replenished at intervals and if the interval between irrigations is lengthy, surface horizons, where rooting is usually dense, may have a low water content and most probably a low relative rate of WU per unit length of root just prior to the soil being replenished by water (Klepper *et al.* 1973; Brown *et al.* 1987).

Interpretations from rain-fed environments are inadequate to improve the efficiency of soil water usage in irrigated crops where water is more readily available and there is a dearth of measurements in the potato crop. It is also necessary to establish whether the efficiency of the root system with respect to WU is the same at every depth and whether it alters during the course of the crop's life. Although ageing of roots may affect their ability to take up water, Taylor & Klepper (1975) indicated that cotton roots at all depths were equally effective in taking up water when compared at equivalent soil and plant water potentials. Taylor & Klepper (1973) also showed that maize roots at depth took up water at a faster rate than those near the surface. They suggested that this resulted from the deeper roots being younger, less crowded and located in wetter soil. Asfary *et al.* (1983), working with potatoes, showed that inflow rates of water were at a maximum *c.* 6 weeks after emergence and decreased thereafter, with inflow rates below 30 cm depth being *c.* six times greater than those above 30 cm. However, this would suggest that many potato crops would have access to little water for the greater part of their life, particularly if shallow compaction restricted rooting depth. It seems feasible to suggest that if water is available in the topsoil, plants will preferentially use water higher in the profile, reducing the 'value' of deeper roots. This is obviously very pertinent in irrigated potato crops which will have several wetting/drying cycles in most seasons.

The effect of varying evaporative demand on the distribution of WU with respect to the relative wetness of different horizons must also be considered. The ratio of potential to actual evapotranspiration depends on both the soil moisture deficit (SMD) within the profile as a whole, or within individual horizons, and on the rate of ET (Denmead & Shaw 1962; Bailey & Spackman 1996). The purpose of thoroughly examining the most important aspects of crop root growth which influence crop response to meeting ET under varying environmental conditions is to ascertain the likely contribution of soil water to plant needs. This will improve understanding of the dynamic changes in the WU potential that occur throughout the life of the crop, thereby permitting more efficient use of both soil and irrigation as water supplies to the growing crop.

In order to study the relationships between rooting characteristics and the patterns of water availability in irrigated potato crops which normally fluctuate between wet and dry soil for a considerable period of their life, the neutron probe (NP) was used to measure the WU of contrasting crops in a number of experiments conducted at Cambridge University Farm over the period 1989–1999.

MATERIALS AND METHODS

General

The current paper reports measurements of WU from a series of experiments conducted at Cambridge University Farm (CUF) on a Milton Series soil (Anon. 1983) over the period 1989–99. Some experiments were subjected to natural rainfall (Expts 3, 5 and 8; Tables 1 and 2) but the rest were grown under 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. Global radiation under the rainshelters was reduced by *c.* 23 % (Stalham 1989) but crops appeared normal compared with crops grown outside the shelters. Soil cultivations for all experiments involved ploughing, spring tining and rotavating or power harrowing to 20–30 cm

Table 1. *List of experiments, varieties, irrigation treatments and planting dates*

Expt	Year	Rainshelter	Variety	Irrigation regimes	Planting date
1	1989	Yes	Record	None (Dry) Irrigated at 20 mm SMD 16–44 DAE, then at 40 mm SMD (Moist) Irrigated at 10 mm SMD (Wet)	6 Apr
2	1990	Yes	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)	30 Mar
3	1990	No	Cara; Desiree	Unirrigated Irrigated (CUF†)	23 Mar
4	1991	Yes	Cara; Estima; Record	None (Dry) Irrigated (CUF)	15 Apr
5	1991	No	Cara; Desiree	Unirrigated Irrigated (CUF)	27 Mar
6	1992	Yes	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)	7 May
7	1993	Yes	Cara; Estima	No irrigation (Dry) Irrigated according to CUF (CUF) Irrigated to maintain <25 mm SMD (Wet)	22 Apr
8	1999	No	Saturna; bare soil	Rain only (W1) 18 mm irrigation SMD at 40 mm SMD (W2) 18 mm irrigation at 20 mm SMD (W3) 36 mm irrigation at 20 mm SMD (W4)	16 Apr

* 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.

depth before drawing up ridges with ridging shares, unless the profile was left flat. In Expt 8, the flat beds were two rows wide created by lifting up the ridging bodies as the tractor ran through the plot. Plots were 5 m in length except in Expts 3 and 5 (14 and 11·8 m, respectively) and five rows wide (three harvest rows guarded by a discard row on each side) except in Expt 8 where plots were eight rows wide. Seed tubers were planted using hand dibbers into rows 71·1 cm wide in all experiments except Expt 8 (76·2 cm). Seed size was small (25–35 mm) and consequently planting density was high for the anticipated yield in these experiments (*c.* 65 t/ha). Seed spacing was 20 cm except in Expts 1 and 8 where it was 25 cm and planting depth 9–11 cm. Unplanted bare plots in Expt 8 were kept weed free by sequential doses of residual herbicide.

The experimental design in Expts 1, 2, 4, 5 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 subplots. Experiment 8 was a randomized split-plot design with the four irrigation treatments allocated to the main plots and surface profile (ridge, flat) and crop (Saturna, bare soil) treatments allocated to the subplots. 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 are stated to be significantly different only if the probability of differences occurring by chance were less than 5% ($P<0.05$). All error bars in figures are one standard error (S.E.) in length. The respective degrees of freedom (D.F.) are given in tables where S.E.s are presented.

Irrigation

Irrigation treatments were scheduled using the CUF irrigation scheduling model based on a modified Penman–Monteith ET equation (M. A. Stalham,

Table 2. *Soil texture, cultivation profile, method and amounts of irrigation and rainfall from emergence to final harvest*

Expt	Soil texture	Profile	Irrigation method	Application amounts (mm)	Total applied (mm)	Rain (mm)
1	Very slightly stony sandy loam	Ridge	Drip	Dry, 0	Dry, 0	0
				Moist, 15·3–18·6	Moist, 347	
				Wet, 3·5–10·5	Wet, 453	
2	Stony sandy loam/clay loam	Flat	Drip	Dry, 0	Dry, 0	0
				Dry-Wet, 19·2–22·3	Dry-Wet, 187	
				Wet-Dry, 18·5–21·6	Wet-Dry, 101	
3	Stony sandy loam/clay loam	Ridge	Overhead	Unirrigated, 0	Unirrigated, 0	85
				Irrigated, 25–37	Irrigated, 202	
4	Slightly stony sandy loam/sandy clay loam	Flat	Drip	Estima, Dry, 0	Estima, Dry, 0	0
				Record, Dry, 0	Record, Dry, 0	
				Cara, Dry, 0	Cara, Dry, 0	
				Estima, CUF, 11·9–25·0	Estima, CUF, 209	
				Record, CUF, 11·9–25·0	Record, CUF, 259	
				Cara, CUF, 11·9–25·0	Cara, CUF, 306	
5	Slightly stony sandy loam/sandy clay loam	Ridge	Overhead	Unirrigated, 0	Unirrigated, 0	183
				Irrigated, 15–25	Irrigated, 197	
6	Stony sandy loam/sandy clay loam	Flat	Drip	W1, 0	W1, 0	0
				W2, 18·3–25·9	W2, 187	
				W3, 20·0–23·8	W3, 229	
				W4, 10·0–21·3	W4, 144	
				W5, 20·0–25·9	W5, 313	
				W6, 6·6–21·3	W6, 354	
7	Stony sandy loam	Flat	Drip	Cara, Dry, 0	Cara, Dry, 0	0
				Cara, CUF, 11·8–20·2	Cara, CUF, 335	
				Cara, Wet, 3·3–11·5	Cara, Wet, 378	
				Estima, Dry, 0	Estima, Dry, 0	
				Estima, CUF, 11·8–20·2	Estima, CUF, 216	
				Estima, Wet, 3·3–11·5	Estima, Wet, 265	
8	Stony sandy loam	Ridge; Flat	Overhead	W1, 0	W1, 0	271
				W2, 16·9–18·6	W2, 107	
				W3, 16·6–19·2	W3, 179	
				W4, 31·2–40·5	W4, 358	

unpublished). The 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), thermistors measuring dry and wet bulb temperature (Grant Instruments), a screened relative humidity sensor (Skye Instruments Ltd) and a solarimeter measuring total incident global radiation (Delta-T Devices Ltd). An atmometer with a canvas cover (Etgage Company) was used as a rapid method of estimating ET for irrigation scheduling in some experiments until meteorological data could be downloaded.

Overhead irrigation was applied through a boom (RST Irrigation) fitted with flat fan nozzles spaced at 2 m projecting in a horizontal plane from both sides of the boom (Expts 3 and 5) or cone nozzles spaced at 1 m pointing vertically downwards (Expt 8). The boom was pulled through the experiment at a pre-set constant speed by a hose reel (Perrot SA, SH63/280). Mean irrigation amounts were estimated from multiple raingauges per irrigation treatment, situated at ground level and not shielded by foliage. Drip irrigation was applied with 17 mm diameter solid wall, pressure-compensated dripper lines, with drippers at 30 cm spacing discharging 1·6 litres/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 and held *in situ* with pegs. The off-setting was to prevent water dripping down the outside of NP access tubes. Irrigation amounts were calculated based on flow meter readings and the spacing of the drippers.

Rooting depth

Rate of vertical root growth was determined from periodic observations of rooting depth using profile pits. At 50% plant emergence pits were dug by hand using a spade across two harvest rows and maximum rooting depth recorded under both rows. The pits were enlarged both vertically and down the length of the plot using a spade or JCB digger, leaving two discard plants between each successive digging. Measurements were taken from the top of the ridge or the soil surface for flat plantings.

Neutron probe measurements

Throughout the course of the experimental series, a Soil Moisture Probe Type IH II (Didcot Instrument Co. Ltd) was used to measure changes in soil water content (SWC). Aluminium access tubes of 45 mm external diameter were gently hammered 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 row centre approximately 1 m in from the end of the plot, with a single tube per plot. This spatial installation assumes that WU and infiltration are uniform across the width of the module used. The NP measures SWC within a radius of 15 cm in wet soils to 30 cm in dry soils (Bell 1987) and therefore a single access tube will not measure the water content on widely-spaced row crops such as potatoes. In order to ensure that the NP measurements represented the whole row-width, four access tubes were installed in each plot in Expt 8. In the ridge plots, the tubes were installed in the ridge centre (RC); one-third of the distance between ridge centre and furrow centre (RF); two-thirds of the distance between ridge centre and furrow centre (FR); and in the furrow centre (FC). In the flat plots, the tubes were installed in the equivalent positions to the ridge plot: the RC tube being in the row centre; the FC tube midway between rows, whilst the RF and FR tubes were one-third and two-thirds the distance respectively from the RC to the FC tube (Gaze *et al.* 2002). Access tubes were installed in the two central rows of each plot to avoid the excessive soil disturbance created by installing four tubes in the same ridge. A portable gantry spanning four rows was used which enabled the NP readings to be taken without damage to the soil surface or crop near the access tubes. In earlier experiments, a $1 \times 0{\cdot}25$ m board was used to spread the weight of the operator on the soil when approaching the access tube. Single readings of 16 s duration were taken at 10 cm intervals down the tubes to 90–150 cm depth relative to the top of the ridge in the ridge plots, or to the soil surface in the flat plots. An horizon-based integration was used to calculate the water content of the profile down to the maximum depth of measurement. For the data presented in this paper, measurements were taken immediately prior to irrigation events and at the same time of day whenever possible.

RESULTS

The NP was used for measuring changes in soil water content in all the experiments but the results must be interpreted with care, since Gaze *et al.* (2002) showed that the NP was inconsistent in measuring known irrigation or rainfall input, even when multiple access tubes were used to ensure the entire row width was sampled. They found that the NP was unable to detect all the water applied to the soil, particularly where the water was largely confined close to the soil surface. Replicated measurements of the change in SMD in the field experiment were precise for a given event and treatment but were not accurate when compared against the input measured in raingauges. It was concluded, therefore, that the NP could not be used reliably to measure changes in soil water storage immediately following irrigation or substantial rain. For periods when there were minimal inputs of water, there was a closer correlation between changes in SMD measured by the NP and those predicted by a modified Penman–Monteith equation than after substantial inputs of water. However, the frequency of NP measurements taken in most of the reported experiments was such that many periods of minimal or zero water input could be used to determine the location of WU and the changes in soil water content can be regarded as accurate within the measurement zone of the NP.

Water uptake and rooting depth

It is important to establish whether the maximum depth of rooting coincides with the maximum depth of measured water uptake and whether the drying front moves downwards at the same rate as roots. Experiment 2 showed that there were differences between irrigation treatments in the time lapse between emergence and measuring water uptake in each consecutive 10 cm horizon down the profile (Fig. 1). In Dry-Dry crops, the average rate of rooting (interpolated from measurements taken at emergence and 80 days after emergence (DAE)) was 1·35 cm/day, whilst WU data from the NP suggested that the rate of downward movement of the drying front to 110 cm (the maximum depth of recording) was 1·30 cm/day. Similarly, in Wet-Dry plots which were irrigated from planting until 44 DAE, the downward movement of the uptake front (1·16 cm/day) was the same as the rate of vertical root growth (1·15 cm/day), but there was a lag before WU was measured in each horizon compared with Dry-Dry crops. However, in the Dry-Wet crops, the rate of rooting (1·11 cm/day) was faster than the measured increase in the depth of drying front (0·93 cm/day) taken over the first 80 DAE.

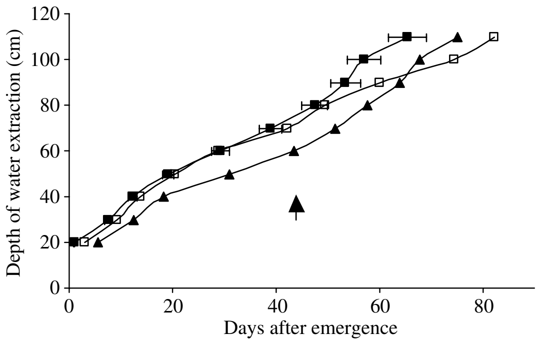

Fig. 1. Time taken for neutron probe to register water extraction at different depths in Expt 2. Dry-Dry (■); Dry-Wet (□); Wet-Dry (▲). Arrow marks change between Dry-Wet and Wet-Dry irrigation regimes.

Additionally, the rate of increase in depth of water extraction followed the same pattern as Dry-Dry crops until irrigation was started 44 DAE. From this point, the downward progression of the drying front slowed compared with unirrigated crops, indicating clearly that soil moisture conditions directly affect the distribution of WU.

In Expts 6 and 7, there were more measurements of rooting depth throughout the season, so it was possible to examine the relationship between rooting depth and depth of WU more closely. Figures 2 and 3 show the fitted linear relationships of depth of WU and rooting depth against time after emergence. Some of the changes in soil water content at shallow depths early in the season were due to evaporation from bare soil rather than root uptake. In Expt 6, rates of rooting across all irrigation treatments were slow (*c.* 0·81 cm/day) owing to shallow compaction. Over the first 25–35 DAE rooting depth was deeper than depth of extraction (Fig. 2). However, following this period, the drying front extended faster than the rooting front, so that water was extracted from deeper than the maximum depth of rooting. The rate at which the drying front progressed down the profile was fastest for unirrigated crops (W1), slower for crops irrigated according to the CUF schedule (W2) and slowest for the crops maintained at an SMD of 10–25 mm (W6; Fig. 2). Since the rate of root penetration was the same for these three irrigation treatments, the unirrigated crop was extracting water from further ahead of the rooting front than either irrigated crop, and, therefore, it can be assumed that the frequently irrigated crops did not fully utilize the lower part of the rooting system since they could extract sufficient water from the moist soil in superficial horizons. Later in the season, crops grown under all irrigation regimes were extracting water from 90 cm, even with frequent irrigation being applied to the soil surface as found in Expt 2.

In Expt 7, it was found that in unirrigated crops the drying front also moved faster down the profile than

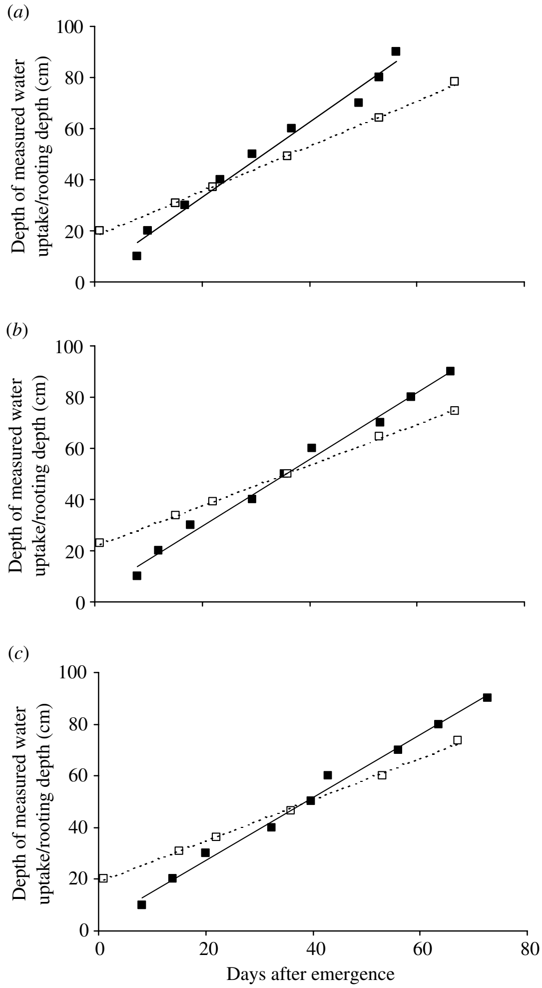

Fig. 2. Relationship between depth of measured water uptake and rooting depth for three contrasting irrigation regimes in Expt 6. (*a*) W1; (*b*) W5; (*c*) W6. Equations of water uptake (—■—) regressions: (*a*) $y = 1{\cdot}47x + 3{\cdot}7$, $R^2 = 0{\cdot}98$; (*b*) $y = 1{\cdot}30x + 3{\cdot}5$, $R^2 = 0{\cdot}99$; (*c*) $y = 1{\cdot}22x + 2{\cdot}8$, $R^2 = 0{\cdot}99$. Equations of rooting depth (---□---) regressions: (*a*) $y = 0{\cdot}88x + 18{\cdot}1$, $R^2 = 0{\cdot}99$; (*b*) $y = 0{\cdot}79x + 21{\cdot}9$, $R^2 = 0{\cdot}99$; (*c*) $y = 0{\cdot}80x + 18{\cdot}8$, $R^2 = 0{\cdot}99$.

the rooting front, so that by 62 DAE Dry crops were extracting water from *c.* 25 cm deeper than the measured depth of rooting (Fig. 3). However, in the CUF crops maintained at an SMD of *c.* 25–48 mm, the drying front extended at the same rate as rooting depth, but for most of the season was *c.* 17 cm shallower than the maximum depth of rooting.

Spatial variability of measurement of water uptake

In order to understand WU more effectively, it is necessary to establish the uniformity of uptake within

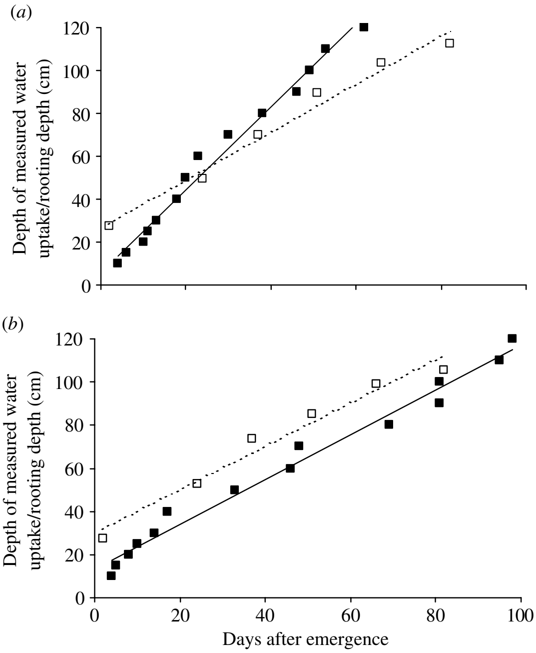

Fig. 3. Relationship between depth of measured water uptake and rooting depth for two contrasting irrigation regimes in Expt 7. (*a*) Cara, Dry; (*b*) Cara, CUF. Equations of water uptake (—■—) regressions: (*a*) $y = 1{\cdot}93x + 5{\cdot}9$, $R^2 = 0{\cdot}98$; (*b*) $y = 1{\cdot}04x + 13{\cdot}4$, $R^2 = 0{\cdot}98$. Equations of rooting depth (---□---) regressions: (*a*) $y = 1{\cdot}12x + 26{\cdot}4$, $R^2 = 0{\cdot}98$; (*b*) $y = 1{\cdot}01x + 30{\cdot}0$, $R^2 = 0{\cdot}97$.

each horizon. To this end, individual access tube locations in Expt 8 were used to test (a) if there were differences in water inputs and/or use between positions and (b) if it was possible to predict the mean SMD from measurements taken at a single position (in particular the RC position since this is the most common position measured). It is important that any relationships derived between a single position and the mean apply throughout the season if they are to be of practical use.

In both unirrigated and irrigated crops, the overall mean SMD from the four tube positions measured in Expt 8 was the same for ridge and flat profiles (Fig. 4). This is significant in that cropping profile had no effect on overall water use, whether the soil was dried out considerably or kept much wetter. There was no evidence of an inherently poorer capture of water following irrigation on ridges compared with a flat profile. However, in unirrigated crops, the RC tube always recorded a greater SMD than other positions and this difference increased when dry soils were wetted with rainfall later in the season. There was a larger difference between the SMD at RC than the other positions under ridge cropping than under flat profiles. When irrigation was applied, the absolute and relative differences in SMD between tube positions were dynamic throughout the season, i.e. there was no way of predicting the mean SMD from any single tube position, or any combination of two tubes, since the relationship between the SMD measured at different positions altered during the season (Fig. 5).

Differences in water use between the access tube positions were best examined for periods when there was no irrigation and minimal rainfall and the crop had full ground cover. There were two periods (beginning 15/16 June and 6/7 July) when the crop had full ground cover and the patterns of water use across the rows could be studied without undue interference from irrigation or rainfall inputs. However, even for these periods, there was a complicating irrigation input which meant data could not be compared between all irrigation treatments over the same number of days. On both occasions, treatments W3 and W4 were irrigated the day before regular weekly NP readings. Pre- and post-irrigation readings were taken for the cropped plots in these treatments but data for W1 and W2 were not taken until the next day, when the whole experiment was monitored. To compare drying patterns, data for W1 and W2 were those collected from the regular weekly monitoring (15/16–22/23 June, 6/7 July–13/14 July) and for W3 and W4 were from the beginning of the period until pre-irrigation readings (15/16–21 June, 6/7–12 July). It has been assumed that the effect of a single extra day's water use would have minimal influence on the patterns of water use between flat and ridge profiles and these can, therefore, be compared. Comparison between irrigation treatments, however, could not be made. Also, for the period beginning 15 June, water use was calculated only over the top 50 cm to exclude slow drainage from the lower depths over the period.

Changes in water storage were consistent for different positions in the bare soil plots but not in the cropped treatments (Table 3). The different water use across rows for the cropped treatments was, therefore, a consequence of crop water extraction and not evaporation from the soil surface. For both periods there was no significant difference between ridge and flat profiles in the mean change in water stored in the profile (Table 4). However, the pattern of water use across the rows differed between ridge and flat, and the pattern was different for the two periods. For the period beginning 15/16 June, the change in water stored at the RC position was the same in ridge and flat profiles (Table 4). The change in water stored at the RF, FR and FC positions with respect to the RC position was significantly less in the flat profiles than in the ridge, with the difference increasing with increasing distance from the RC position. This suggests that the crop extracted water more uniformly across the row-width in the flat profiles than in the ridged plots. A different pattern of water use was observed for the period beginning 6/7 July (Table 4). Water use

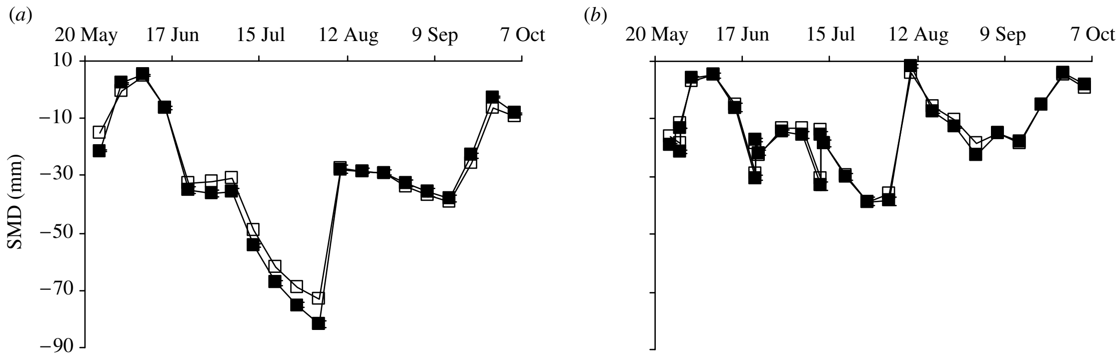

Fig. 4. Soil moisture deficits in cropped plots calculated from the mean of four access tube positions in Expt 8. (*a*) W1; (*b*) W3. Flat (■); Ridge (□).

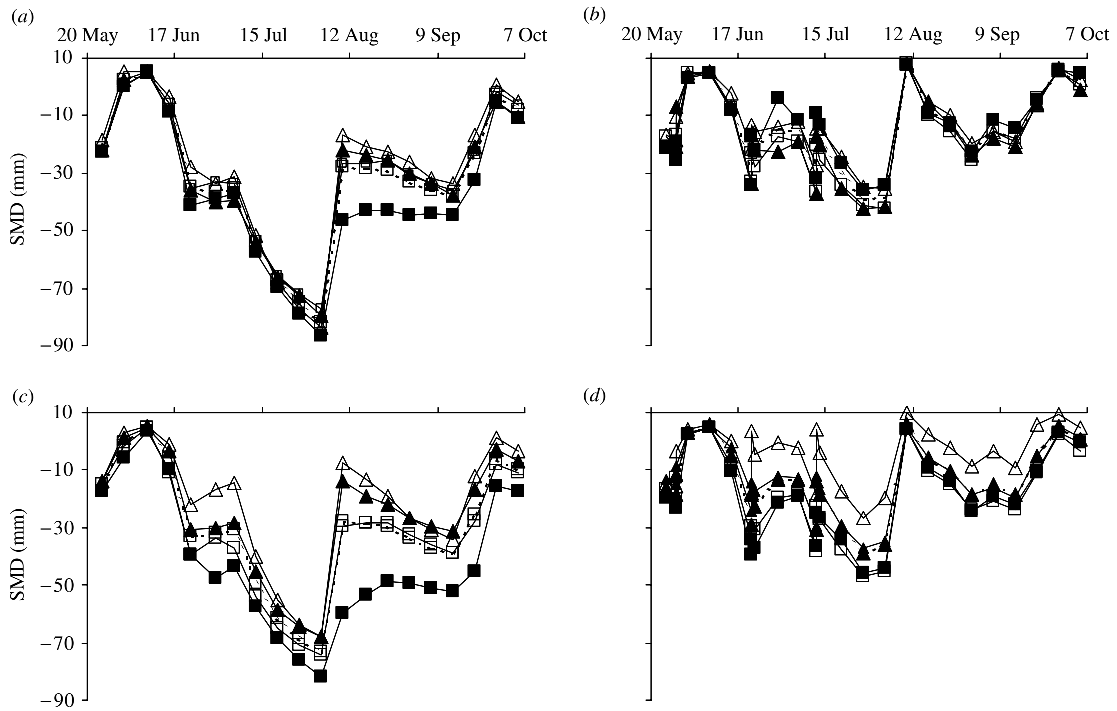

Fig. 5. Soil moisture deficits in cropped plots measured at different tube positions in Expt 8. (*a*) Flat W1; (*b*) Flat W3; (*c*) Ridge W1; (*d*) Ridge W3. RC (■); RF (□); FR (▲); FC (△); Mean (- - - -).

at the RC position was less in the ridge profile than in the flat. Water use at the FC position with respect to the RC position was greater under ridges than on the flat but there were no significant differences at the RF and FR positions. Again the crop appeared to extract water more uniformly across the row-width in the flat profiles than when grown on ridges. The conclusion from both these monitoring periods is that traditional ridge profiles give rise to a spatial heterogeneity of WU and this pattern changes throughout the season. Planting crops on the flat, by contrast, resulted in a more homogeneous uptake across the profile and a greater stability of this pattern over time but the overall water use and productivity were the same irrespective of cultivation profile.

The contribution of each depth to the overall SMDs measured at the beginning and end of the two periods is shown in Fig. 6. For the period beginning

Table 3. *Nominal change in water stored in the soil profile (mm) under cropped and bare treatments measured by the neutron probe over a 7-day period beginning 15 June in Expt 8. Data are means of W1 and W2 irrigation treatments and ridge and flat treatments*

	RC*	RF–RC	FR–RC	FC–RC	Mean
Crop	30·0	−2·4	−4·1	−9·7	26·0
Bare	5·2	0·9	0·1	−0·6	5·3
S.E. (12 D.F.)	1·05	0·87	1·15	1·39	0·72

*RC, RF, FR and FC are positions from ridge centre to furrow centre (see text for details).

Table 4. *Nominal change in water stored in the soil profile (mm) measured at different positions across the row under cropped treatments over two 5–7-day periods in Expt 8. Data are for the top 50 cm of the soil profile for the period beginning 15 June and to 100 cm depth for the period beginning 6 July*

Period	RC*	RF–RC	FR–RC	FC–RC	Mean
Beginning 15 June					
Ridge	29·3	−4·1	−6·6	−13·5	23·2
Flat	26·7	−0·3	−1·2	−6·2	24·8
S.E. (8 D.F.)	0·96	0·79	1·11	1·60	0·66
Beginning 6 July					
Ridge	16·0	2·9	2·4	5·0	18·5
Flat	21·8	0·3	−0·4	−3·2	20·9
S.E. (8 D.F.)	1·24	1·94	1·98	2·31	0·78

*RC, RF, FR and FC are positions from ridge centre to furrow centre (see text for details).

15/16 June, although the overall water use was similar between the flat and ridge profiles, the pattern of water extraction differed both horizontally and vertically. In the ridge profiles, water use decreased as the distance from RC increased. In flat profiles, position FC had a smaller WU than other positions at all depths below 10 cm, with water use over the period at the RC, RF and FR positions being very similar for a particular depth. Although there were no 10 or 20 cm depths for the FR and FC positions in the ridge profile, this was compensated by increased water use from under the RC and RF positions. The slower water use observed over the period beginning 15/16 June (33 days after 50% emergence) in the FC position compared with RC in both ridge and flat profiles could have been partly caused by differences in rooting density, since Stalham & Allen (2001) showed that it took 37 days after 50% emergence before rooting density became horizontally homogeneous for a given depth between the RC and FC positions. Assuming the same to be true in Expt 8, it can be argued that soil water conditions and crop demand were such that the roots were able to supply most of the crop demand from soil closer to the RC position during this period but that poorer rooting density reduced WU underneath the furrow.

For the period beginning 6 July, overall water use in ridge profiles was greater underneath position FC than RC as a consequence of increased uptake between 30 and 50 cm (Fig. 6). This reversed the trend in WU across the profile observed in the period commencing 15/16 June. By contrast, the flat profile had the same pattern of WU as the earlier period, with position FC having a slower WU than the other positions. Although the patterns of WU between the monitoring positions changed, overall water use was still the same between ridge and flat profiles.

Water uptake in different horizons following re-wetting

The summer of 1990 was exceedingly hot, with temperatures reaching 35·6 °C on 5 August. There were 6 days when potential ET from a full canopy exceeded 6 mm/day and 18 days when it exceeded 5 mm/day. Correspondingly, the requirement for irrigation was large. In Expt 3, the absence of rainfall in June meant that unirrigated crops failed to reach full ground cover, thereby limiting the atmospheric demand for water compared with irrigated crops. Figure 7 shows the progression of SMD in each horizon in Cara crops as the rooting system deepened. There was a progressive drying down the profile as roots extracted water sequentially from each horizon. Even though horizons closer to the surface only had a small fraction of their easily available soil water depleted by root uptake, WU was observed in deeper horizons. In unirrigated crops, WU at 80–90 cm was observed as early as late June. The soil dried progressively during August until 16 mm of rain fell on 14–19 August, when the 10 and 20 cm profiles were re-wetted. Following this rain, WU at 80 and 90 cm still continued, showing that root activity was maintained even though a large part of the daily evapotranspiration demand was satisfied by soil water reserves closer to the soil surface. The irrigated Cara crops were slower in extracting water at depth, only starting to extract water at 80–90 cm at the beginning of August. The irrigation system could not cope with the extreme evapotranspiration demand on the crop during mid-August and the total SMD in irrigated Cara exceeded 50 mm during this period (Fig. 8). The results for the shallower rooting, more determinate variety Desiree are shown for comparison. Even though the irrigation system was applying 23 mm/week during this period and the 10 and 20 cm horizons were getting increasingly wetter, mid-profile horizons (40–60 cm) maintained their soil

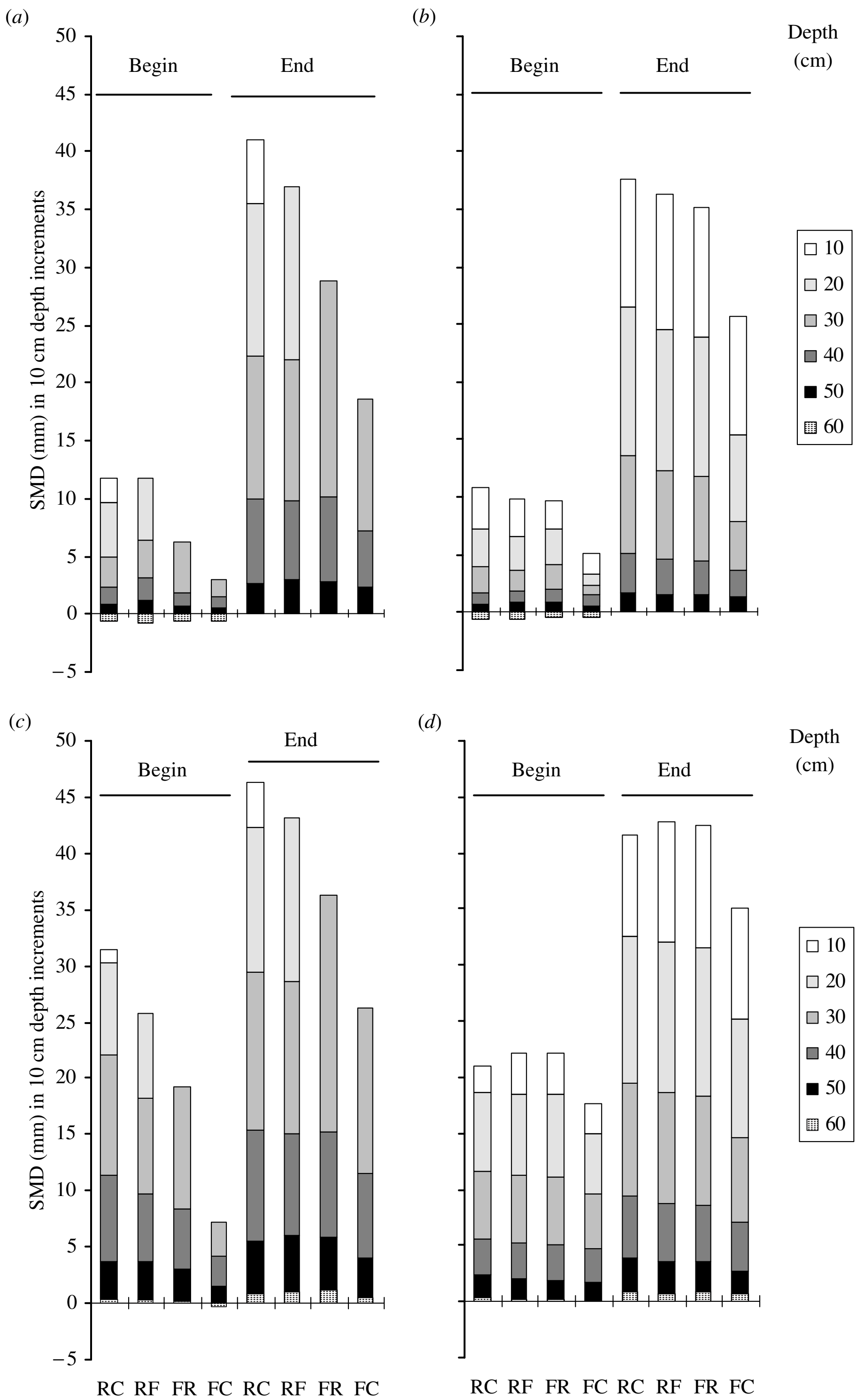

Fig. 6. For legend see opposite page.

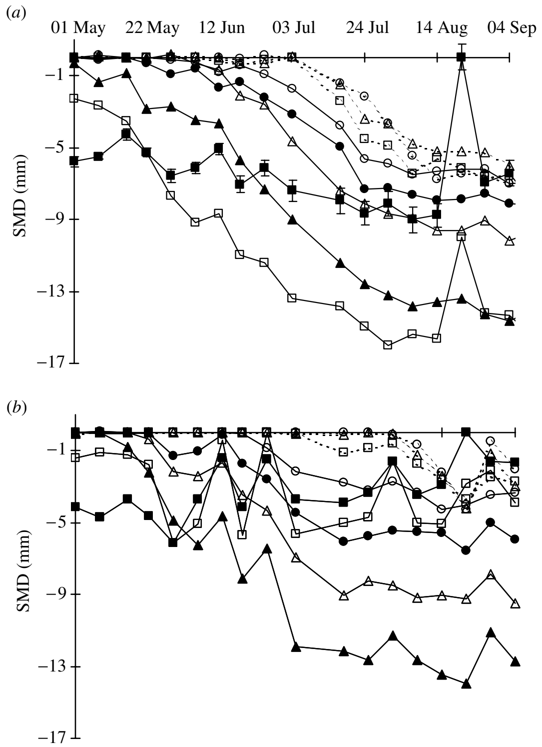

Fig. 7. Horizon soil moisture deficits in (*a*) unirrigated Cara and (*b*) irrigated Cara in Expt 3. 10 cm (–■–); 20 cm (–□–); 30 cm (–▲–); 40 cm (–△–); 50 cm (–●–); 60 cm (–○–); 70 cm (- -□- -); 80 cm (- -△- -); 90 cm (- -○- -) depths.

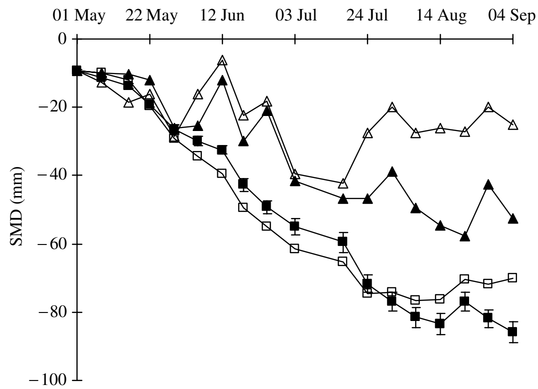

Fig. 8. Total soil moisture deficits in Expt 3. Unirrigated Cara (■); Unirrigated Desiree (□); Irrigated Cara (▲); Irrigated Desiree (△).

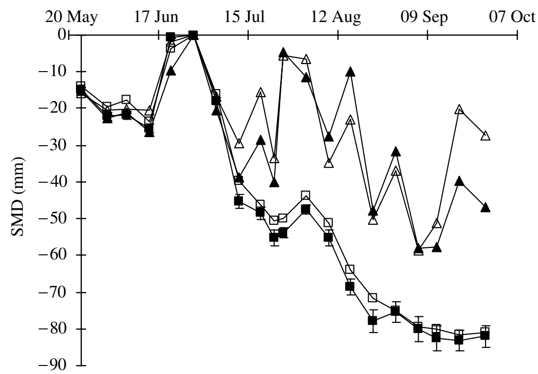

Fig. 9. Total soil moisture deficits in Expt 5. Unirrigated Cara (■); Unirrigated Desiree (□); Irrigated Cara (▲); Irrigated Desiree (△).

water content, whilst at 70 cm and below uptake continued at a rapid rate.

By contrast, the summer of 1991 was cooler and wetter than 1990. June had plentiful rain (98 mm) which meant that unirrigated crops in Expt 5 achieved complete canopy cover. However, July, August and September were drier than average but nearly half of the rain that fell over this period occurred on 31 July and 1 August (44 mm) and it failed to rain on 68 days during July–September. As a consequence, SMDs began to increase rapidly in unirrigated crops from the beginning of July, eventually reaching *c.* 80 mm in both Cara and Desiree (Fig. 9). All crops took up water from 80, 90 and 100 cm depths, with the 'lag phase' of WU from deeper horizons following in irrigated as well as unirrigated crops (Fig. 10). Water uptake during August was occurring in irrigated crops simultaneously at depths below 80 cm and in superficial horizons which were being periodically replenished with irrigation.

Efficiency of water extraction from different horizons under contrasting irrigation regimes

The Wet crops in Expt 1 were maintained at an overall SMD of <10 mm, yet water was still extracted from as deep as 90 cm. Owing to the frequent irrigation of these wet treatments, superficial horizons were

Fig. 6. Nominal soil moisture deficits (SMD) measured in 10 cm increments down the soil profile at four positions across the row width for cropped ridge and flat profiles at the beginning and end of two 5–7 day periods in Expt 8. (*a*) ridge, period beginning 15 June; (*b*) flat, period beginning 15 June; (*c*) ridge, period beginning 6 July; (*d*) flat, period beginning 6 July. Data are means of all irrigation treatments.

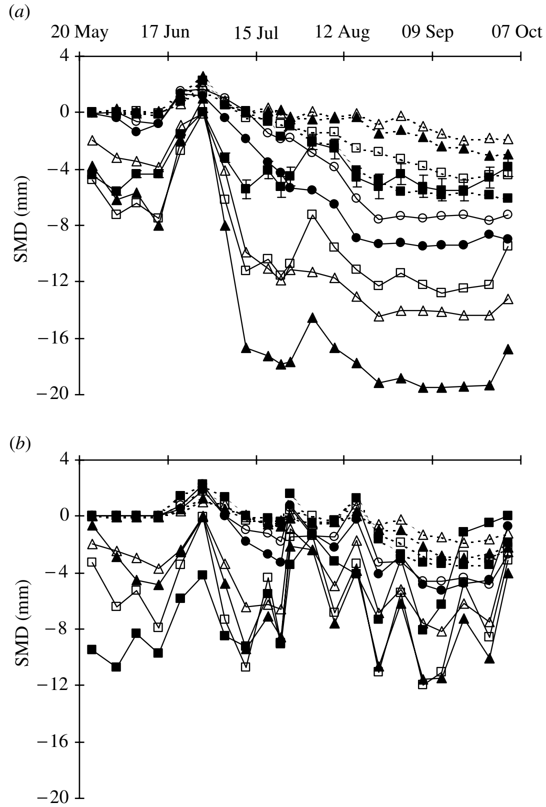

Fig. 10. Horizon soil moisture deficits in (*a*) unirrigated Cara and (*b*) irrigated Cara in Expt 5. 10 cm (–■–); 20 cm (–□–); 30 cm (–▲–); 40 cm (–△–); 50 cm (–●–); 60 cm (–○–); 70 cm (- -■- -); 80 cm (- -□- -); 90 cm (- -▲- -); 100 cm (- -△- -) depths.

Table 5. *Effect of irrigation regime on maximum soil moisture deficit (mm) in different horizons in Expt 1*

Horizon (cm)	Irrigation regime Dry	Moist	Wet	S.E. (6 D.F.)
0–10	4·5	4·3	1·4	0·59
10–20	10·9	8·9	3·3	0·59
20–30	12·1	8·0	5·7	0·67
30–40	12·5	7·9	6·1	1·01
40–50	13·1	7·1	6·3	0·95
50–60	12·3	6·0	5·0	0·91
60–70	11·9	5·9	4·4	1·33
70–80	10·0	6·1	4·2	1·24
80–90	7·0	6·0	4·4	1·23

Table 6. *Effect of irrigation regime on maximum soil moisture deficit (mm) in different horizons in Expt 2*

Horizon (cm)	Irrigation regime Dry-Dry	Dry-Wet	Wet-Dry	S.E. (6 D.F.)
0–10	5·5	4·5	4·6	0·34
10–20	14·7	11·6	13·8	0·74
20–30	12·8	10·5	13·0	0·26
30–40	10·1	9·3	10·8	0·49
40–50	8·7	5·7	7·9	0·83
50–60	7·7	4·5	6·3	0·95
60–70	6·6	3·7	6·0	0·63
70–80	6·0	2·7	6·0	0·52
80–90	6·4	3·2	6·3	1·00
90–100	6·1	3·0	6·3	0·93
100–110	5·8	2·9	6·1	0·91

maintained at, or over, field capacity for much of the season, nevertheless the drying front progressed downwards at a rate comparable with the rate of rooting. The results from this experiment also show that on homogeneous soils crops can extract similar quantities of water from each horizon, with irrigation regime changing the magnitude of the amounts extracted compared with unirrigated crops (Table 5). Superficial horizons did not need to be exhausted before significant WU was observed in deeper horizons. These results, therefore, support those obtained from the uncovered Expts 3 and 5.

Where the profile had markedly dissimilar top- and subsoils, with moderately water-retentive topsoils but very stony sand subsoils (Expt 2), less water was extracted at depths below the ploughed layer than in shallow horizons but crops irrigated for the first 44 DAE and then forced to exist on soil reserves could still exhaust deeper horizons as completely as crops grown without any water (Table 6).

Relationship between water uptake and rooting density

Figure 11 shows the comparison between the proportion of TRL in each horizon and the proportion of total WU contributed by each horizon for three sample periods in Expt 7 for Dry and Wet Cara. Changes over time in proportional WU from a particular horizon did not follow the changes in RLD in each horizon. At the earliest sampling, when the soil was wet in most horizons except those closest to the surface (18–25 DAE), the proportion of total WU at a particular depth over a 7-day period corresponded reasonably closely with the proportion of TRL in the horizon. As the soil was dried out in surface horizons, root activity with respect to WU decreased unless the horizon was replenished with irrigation. Dry crops were forced to exist on soil water alone and as the season progressed the proportional contribution to uptake by lower horizons bore no resemblance to the rooting density (see specific root

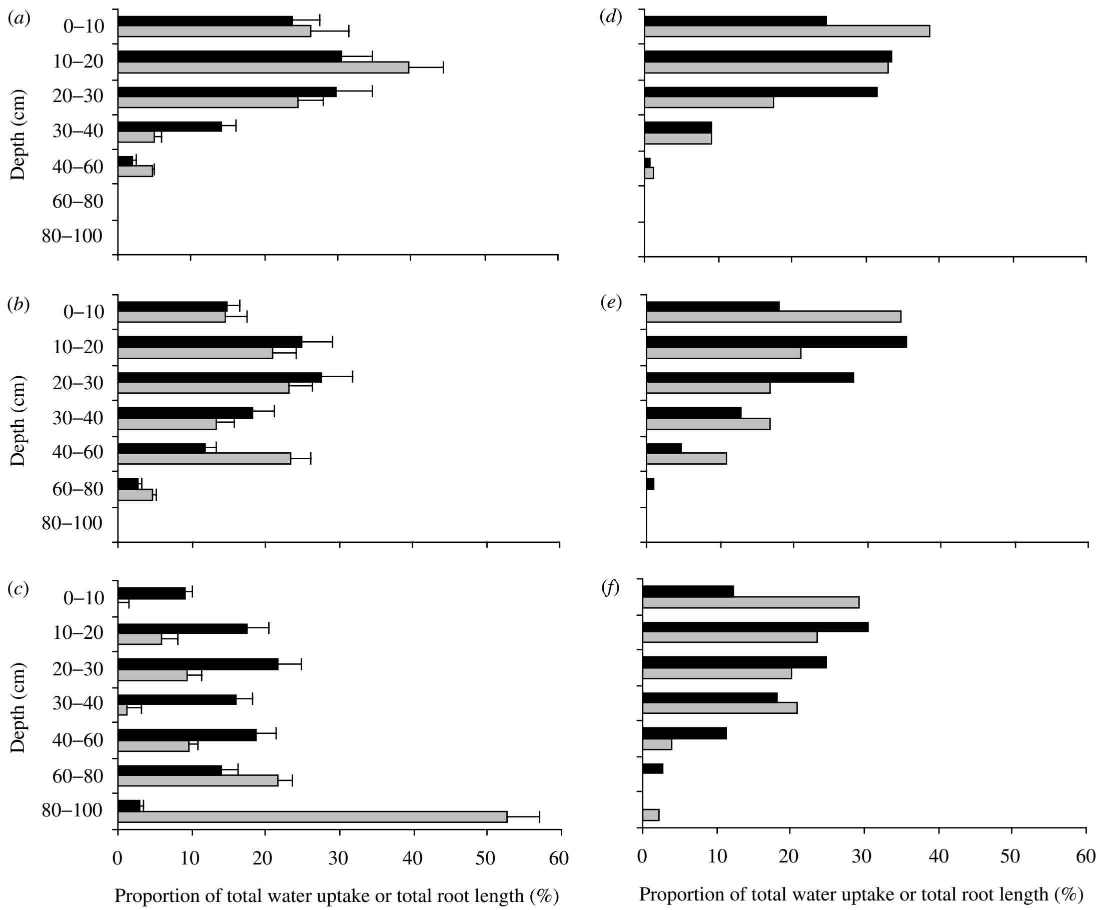

Fig. 11. Proportion of total root length and total water uptake in different horizons on the three sampling dates in Expt 7 (Cara, Dry and Wet only). (*a*) Dry, 18–25 DAE; (*b*) Dry, 34–41 DAE; (*c*) Dry, 76–83 DAE; (*d*) Wet, 18–25 DAE; (*e*) Wet, 34–41 DAE; (*f*) Wet, 76–83 DAE. Root length (■); water uptake (▧).

activity in next section), with a very small root length contributing massively to WU. In crops which were frequently irrigated (Wet) and the surface horizons were replenished every 2·3 days on average, there was the closest correlation between uptake and RLD. As the interval between irrigation events widened (4·5 days in CUF-scheduled crops), the correlation weakened, since plants drew increasingly on water reserves deeper (i.e. >30 cm depth) in the profile as the season progressed (data not shown in Fig. 11). It appeared that these deeper roots could satisfy demand sufficiently, since total and tuber dry matter yields were not significantly different between CUF and Wet treatments for each variety. Root death caused RLD to decrease in the shallowest horizons by 40–50 DAE and this was particularly severe where irrigation was withheld but it also occurred in irrigated treatments to a lesser degree (Stalham & Allen 2001).

Specific root activity

Tables 7 and 8 show WU per unit length of root throughout the profile from two (Expt 6) or three (Expt 7) sampling periods for different irrigation regimes and varieties. In irrigated crops, rates of specific inflow decreased as depth increased from the surface to 40–50 cm but the deepest horizon where roots were present often had high inflow rates. Where water was withheld during the sampling period, uptake rates in the shallowest horizons were less than those in deeper horizons. Inflow rates in the shallow horizons were generally greater than measured by Asfary *et al.* (1983) when comparing the same period after emergence (Table 8b). Their rates in unirrigated crops between 28 and 42 DAE were 17×10^{-4} cm^3/cm/day above 30 cm and 83–113 $\times 10^{-4}$ cm^3/cm/day below 30 cm. Activity per unit length of root in the current

Table 7. *Effect of irrigation regime on rate of water uptake per unit length of root* ($\times 10^{-4}$ $cm^3/cm/day$) *in different horizons during two periods in Expt 6*. (*a*) *51–56 DAE*, (*b*) *78–83 DAE*. (*Horizons with negative values became wetter during period studied*)

Depth (cm)	Irrigation regime† W1	W2	W3	W4	W5	W6	S.E. (10 D.F.)
(a)							
0–10	10·7	31·3	46·3	27·0	18·1	37·7	4·86
10–20	5·6	8·8	39·5	41·0	47·3	26·7	5·53
20–30	7·6	10·7	28·9	42·9	43·9	28·8	4·65
30–40	25·2	20·4	18·8	25·9	30·9	19·8	4·49
40–60	30·4	15·5	2·7	0·6	5·9	13·5	3·47
60–80	69·8	37·3	8·6	41·1	41·4	44·9	14·41
DWU*	1·01	1·08	4·01	3·98	4·08	3·94	0·490
(b)							
0–10	−9·6	59·3	23·8	−3·0	19·3	36·4	8·99
10–20	1·6	42·7	24·3	3·9	22·8	36·5	6·83
20–30	6·0	17·9	18·0	1·6	9·5	1·3	2·98
30–40	7·5	33·7	7·7	4·4	5·9	−6·3	3·32
40–60	15·7	61·3	17·6	5·6	11·4	−9·2	5·00
60–80	17·7	45·3	21·3	15·6	13·8	14·0	6·56
80–100	17·0	178·6	4563·4	–	687·5	45·5	220·73
DWU*	0·47	2·97	2·78	0·40	2·44	2·67	0·454

* DWU = daily water use (mm/day).
† See Table 1 for details.

study was very high in some of the lower horizons, compensating to a large extent for the lower rooting density but the errors involved in sampling roots mean that these data must be treated with caution.

Crops receiving irrigation at the time of sampling had higher inflow rates in the upper 30 cm of the profile than those kept dry but where crops were irrigated after substantial drying periods (e.g. W2 in Table 7a), root activity was re-established in the upper profile with a subsequent decrease in activity below 40 cm. Crops exposed to this irrigation regime were still able to take up water at the same rate as fully irrigated crops despite being droughted for 44 DAE (Table 7b).

Crops maintained at low SMDs throughout the season (e.g. W6, Table 7; Wet, Table 8) had a similar overall water use to those kept at higher SMDs (e.g. W5, Table 8), although the pattern of WU down the profile differed slightly. In Expt 6, the activity of roots in the 10–40 cm horizons was higher in W5 than in W6 at the earlier sampling (Table 7). Later in the season in this experiment, activity in the top 20 cm of soil was less in W5 than W6 but not significantly so. In Expt 7, the activity of roots in the top 40 cm of soil was similar for the CUF and Wet irrigation regimes, indicating that moderately high SMDs (e.g. 40–45 mm) can be sustained, albeit under moderate ET demand (2–3 mm/day) without WU being compromised. There also appeared to be no difference between Estima and Cara in specific rate of uptake when canopies were of similar size. Estima produced a smaller final TRL than Cara and the root system died earlier but this did not compromise its ability to extract water during the periods studied in Table 8.

Effect of varying evaporative demand on the relationship between actual and potential evapotranspiration at different soil moisture deficits

For a given soil type, the rate of actual ET (AE) depends on the both the SMD and the rate of potential evaporative demand (PE) 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 AE:PE ratio drops below 1·0) for different daily evaporative 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.

In most experiments, measurements of soil water content using the NP were made at frequent intervals

Table 8. *Effect of variety and irrigation regime on rate of water uptake per unit length of root* ($\times 10^{-4}$ $cm^3/cm/day$) *in different horizons during three periods in Expt 7.* (*a*) *18–25 DAE,* (*b*) *34–41 DAE,* (*c*) *76–83 DAE.* (*Horizons with negative values became wetter during period studied*)

Depth (cm)	Variety / Irrigation regime†	Estima			Cara			S.E.
		Dry	CUF	Wet	Dry	CUF	Wet	(10 D.F.)
(a)								
0–10		14·9	41·5	28·2	12·2	28·3	22·1	6·07
10–20		13·0	20·8	15·6	14·5	18·6	13·8	2·39
20–30		6·8	10·3	8·7	9·2	13·0	7·8	2·33
30–40		0·5	9·2	12·4	3·9	5·8	14·1	2·75
40–50		27·3	0	30·6	26·0	0	21·6	11·74
DWU*		0·99	2·08	1·91	1·14	1·82	1·64	0·245
(b)								
0–10		0·6	35·1	33·1	5·6	29·9	29·9	2·63
10–20		5·0	14·0	11·4	4·8	10·6	9·2	2·32
20–30		11·2	14·2	11·2	4·8	11·5	9·3	2·54
30–40		6·3	14·0	25·0	4·1	12·9	20·2	1·78
40–60		12·1	19·5	23·8	11·3	14·7	34·4	6·31
60–80		15·7	11·1	10·2	10·3	16·2	0	4·32
DWU*		0·78	2·38	2·49	0·70	2·22	2·28	0·358
(c)								
0–10		−8·0	46·3	17·7	−0·2	54·8	45·9	4·50
10–20		−1·1	14·7	11·4	1·6	17·5	14·9	2·97
20–30		−0·9	20·9	20·6	2·0	15·1	15·5	2·10
30–40		−4·5	28·7	22·6	0·4	22·9	22·0	3·02
40–60		−3·2	−4·1	10·9	2·4	6·5	6·5	2·99
60–80		1·5	−2·2	5·4	7·2	3·7	0	2·35
80–100		30·0	−6·0	50·0	80·0	12·0	178·0	56·30
DWU*		0·01	2·61	2·31	0·85	3·27	3·27	0·466

* DWU = daily water use (mm/day).
† See Table 1 for details.

(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). The water use of the crop was calculated for these periods and compared with the PE for the crop. Potential ET was estimated from $K_c * ET_0$, where K_c is a function of ground cover, crop height and stomatal conductance and ET_0 is Penman–Monteith reference crop (grass) ET. 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. 12). 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).

Figure 13 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 the 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. 13*a*). However, over the following 3 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 can allow their root systems to access

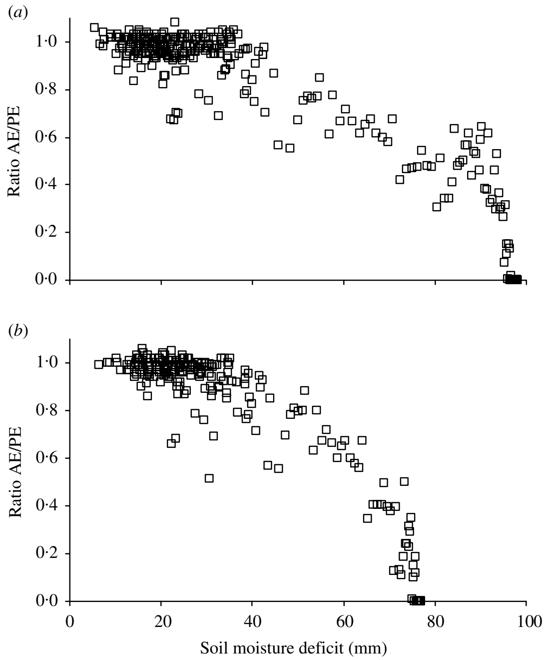

Fig. 12. Relationship between the ratio of actual (AE): potential (PE) evapotranspiration and soil moisture deficit in (*a*) Cara and (*b*) Estima in Expt 7.

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. 13*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 for each variety in each experiment and for all ET_0 values close relationships were found which allowed the limiting deficit to be established and the slopes of the lines either side of the limiting deficit (Table 9). Figure 14 presents the data from Table 9 in a visual form that is easier to interpret but for Cara only to avoid excessive duplication of data.

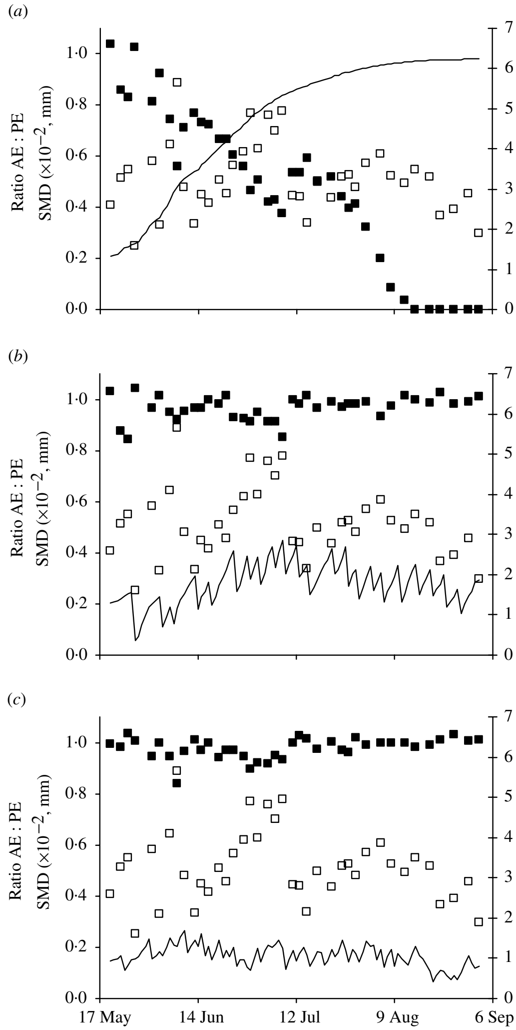

Fig. 13. Ratio of actual (AE):potential (PE) evapotranspiration, mean ET_0 during the measurement period and soil moisture deficit (SMD) in Cara in Expt 7. (*a*) Dry; (*b*) CUF; (*c*) Wet. AE:PE ratio (■); ET_0 (□); SMD (—).

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. 14). Second, 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 9). Third, 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)

Table 9. *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 D.F.

who surmised that crops function at potential (i.e. AE = PE) until the limiting SMD is reached. Clearly, the results from the current study differ from this conclusion. Fourth, 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 and 7, the same type of close relationships were found but as a result of small variation in texture and stone content limiting SMDs were similar. Other varieties also showed similar close relationships (Table 10).

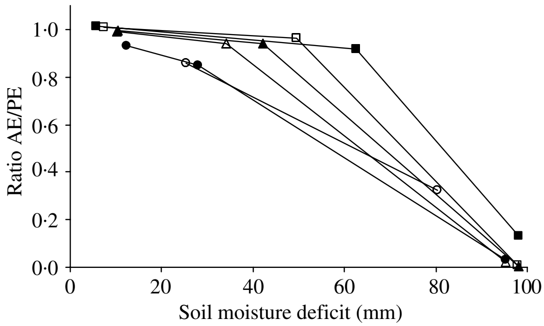

Fig. 14. Relationship between ratio of actual (AE):potential (PE) evapotranspiration and soil moisture deficit for varying daily ET_0 in Cara in Expt 7. ET_0 (mm): 1–2 (■); 2–3 (□); 3–4 (▲); 4–5 (△); 5–6 (●); 6–7 (○).

DISCUSSION

The results presented provide considerable insight into root growth and water uptake in a range of potato crops which have implications for commercial and experimental purposes. All crops rooted to a considerable depth and the variation in final depth was associated with soil conditions. The significance of soil conditions throughout the entire profile cannot be over-emphasized for the contribution of the deepest roots under all water regimes was considerable and much greater than expected. The maximum depths of extraction were considerable (90–120 cm) and these abstraction depths were reached rapidly, typically 55–75 DAE and therefore well before the onset of senescence in maincrop varieties grown in the UK. Roots in deep horizons were found to be capable of taking up water simultaneously with those in the surface horizons irrespective of the soil water content in more superficial horizons, although there was sometimes a lag phase between roots reaching a horizon and then extracting water from it. Crops kept unirrigated for large parts of the season nearly always had a deeper maximum rooting depth than irrigated crops but were considerably sparser in terms of RLD (Stalham & Allen 2001). In such crops, it appeared that roots could extract water from considerable distances ahead of their tips and therefore using maximum rooting depth to assess the depth of water extraction may be an underestimate, especially later in the season. Unless irrigation is excessive and waterlogging or anaerobiosis occurs, soil water status has a much greater effect on the depth of water extraction than on maximum depth of rooting. Durrant *et al.* (1973) observed that depth of water extraction in potatoes was related to, but could be 10–15 cm shallower than, rooting depth, and in the reported experiments many frequently irrigated crops kept

Table 10. *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

close to field capacity (10–25 mm SMD) extracted water from depths shallower than their rooting depth. However, in crops maintained at greater SMDs (*c.* 40 mm), WU was similar to rooting depth and therefore utilized more of the soils' potential to supply water. There was a contrast between Expts 2, 6 and 7 in the relationships between rate of increase of the depth of drying and rate of rooting. In Expt 2, rooting depth was similar to depth of water extraction in two treatments, but greater than the depth of water extraction in the Dry-Wet treatment. In Expts 6 and 7, after *c.* 40 days rooting depth was shallower than WU, except in the CUF-irrigated treatments in Expt 7 where roots were always observed deeper than the drying front. During periods of extreme ET demand the deepest roots contributed to WU, even in crops maintained at small SMDs, since the surface horizons could not completely supply the crops' needs. Maintaining a moderate SMD in the soil encouraged the deepest roots to draw water from ahead of their own depth compared with soils maintained closer to field capacity. This emphasizes the importance of creating favourable soil conditions at planting so that root growth is not impeded and the depth of water extraction is maximized. By early July, the root systems of typical maincrop potatoes should be utilizing most of the water in the top 80 cm of soil. For irrigation scheduling, it is clear that accurate estimates of current water uptake and rooting depths are crucial for estimating the current water status of the crop. As these will change during the season and be influenced by soil conditions in each field (or part of field), improvements in the efficiency of water use require much greater appreciation of the significance of root growth. From this, practical and environmental benefits accrue from improved scheduling.

In unirrigated crops, the RC position was always drier than other positions and these differences increased on re-wetting at the end of the season. In both unirrigated and irrigated crops, the relation between the SMDs measured at each position across the row width altered during the season. A single access tube located in the centre of the ridge clearly does not measure an overall SMD across the profile, however most data on water use in potatoes (Long & French 1967; French *et al.* 1973; Prestt 1983; Ramadan 1986; Jefferies & MacKerron 1987; Singh *et al.* 1993; Hamer *et al.* 1994; Bailey *et al.* 1996) have been taken from the RC position. Since the RC position is the most common location for access tubes for measuring water use in both experimental and commercial potato fields, the water requirement of the crop will be over-estimated.

Although there was no evidence that ridge profiles had any effect on overall WU, the pattern of WU differed across the rows between flat and ridge profiles. Water uptake under ridges was less uniform than under flat profiles but the relationship between different measurement positions changed throughout the season. The increased WU in dry ridge profiles at the FC position compensating for the reduced WU from the RC position is an interesting observation. Preferential WU from wetter parts of the soil compensating for decreased uptake from drier parts of the soil has been reported for kiwifruit vines and other tree or vine species (Green & Clothier 1995). Conversely, pot experiments with apples and maize have shown that when the root system is split between dry and wet soil, the leaf conductance is reduced without significant leaf water deficit (Davies & Zhang 1991). This technique of partial rootzone drying has also been used experimentally and commercially to restrict leaf growth in grape vines and increase irrigation water use efficiency (Dry & Loveys 1999; Dry *et al.* 2000*a*, *b*; Stoll *et al.* 2000). These results for potatoes grown in the field, however, suggest overall plant water use was not restricted by part of the root system being in drier soil as other zones were adequate to meet demand. Furthermore, there were no significant differences in dry matter yield between ridge and flat profiles which would have been expected if the drier ridge RC position limited overall WU.

A gradual progression of the drying front down the profile was observed as water was extracted sequentially from each horizon in turn despite the more superficial horizons having been dried to only a small fraction of their easily available water. Several of the experiments showed that root activity was maintained in the deepest parts of the rooting system even following re-wetting of the upper profile. This demonstrates that once rooting systems have established themselves to considerable depth, WU continues from deeper roots even though upper horizons may be periodically re-wetted by irrigation and that they do not 'switch off', only to resume functioning when the upper profiles dry out again. It was also shown that, in homogeneous soils, roots from unirrigated crops exhausted each horizon to a similar extent, whilst different irrigation regimes merely altered the total amount of water extracted from each horizon, not the relative water use of the horizons, even where soils were maintained close to field capacity. Given sufficient time, crops grown with irrigation for a period then remaining unirrigated for the rest of the season were capable of extracting as much water from all horizons as crops receiving no inputs of water.

It proved impossible to link WU with RLD in specific horizons over the course of the season. Initially (18–25 DAE), the proportion of total WU corresponded reasonably closely with the proportion of TRL in the horizon. Where the soil was allowed to dry out in superficial horizons in unirrigated crops, the proportional contribution to WU made by roots in deeper horizons was far greater than their overall contribution to TRL. However, the overall WU of these crops was low. Where high rates of WU were maintained in frequently irrigated crops there was a closer relation between WU and RLD but as the irrigation interval increased and the soils were maintained at an SMD of 25–45 mm the correlation worsened, since plants increasingly relied on water below 30 cm for growth. It appeared that these deeper roots could satisfy demand since yields were the same for very frequently irrigated crops and those maintained at moderate SMDs. Therefore, it seems that the pattern and extent of soil drying experienced by a crop changes the horizons where it absorbs water at different growth stages and the relative RLD in a particular horizon is not a good indicator of the potential to take up water from that depth. Although RLD decreases rapidly with increasing depth, roots deeper in the profile can contribute a considerable component of total crop water requirement whatever the water status of the superficial horizons close to the soil surface.

In irrigated crops, rates of specific inflow of water to roots decreased as depth increased but roots in the deepest horizon, i.e. those whose root tips were the youngest and growing into wetter soil, had the greatest activity per unit length of root. Whilst it may not contribute much to overall daily WU, the small fraction of rooting in the deepest horizons nevertheless has an important role to play in sustaining WU in periods of high ET demand. Where crops of Cara were irrigated after prolonged periods without water, root activity was re-established in the upper profile with a subsequent decrease in activity below 40 cm. This replenishment of water and absorption by roots close to the surface permitted the crops to maintain the same rate of WU as crops kept fully irrigated throughout the season. This variety clearly can maintain active roots in surface horizons even when the soil dries considerably. Thus, there was no evidence of any serious loss of potential root activity, even in much more extreme conditions than would normally be experienced in practice. Although Expt 6 was not repeated with other varieties, judging from the decrease in RLD in determinate varieties such as Estima grown without irrigation (Stalham & Allen 2001), it seems unlikely in most varieties that sufficient roots would survive prolonged drying periods to enable WU to continue in surface horizons following re-wetting with late-season rainfall or irrigation.

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, an increase in ET_0 will increase the rate of increase in the diffusion pressure deficit of the leaves leading to 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 increases. These 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. actual = potential ET) continues until soil water content is depleted and the limiting SMD is 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 WU 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 versus 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 during their expansion phase 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). The crops maintained at an SMD of 9–15 mm had AE:PE ratios over the same period of 0·89–0·96 in comparison. 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.

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