Final Report

Improving Water Use Efficiency Through Understanding Soil and Plant Water Balance

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1. SUMMARY

Efficiency of water and irrigation usage can be improved by better understanding of how plants balance their water status in relation to evaporative demand under different soil conditions. A three-year project was undertaken by Cambridge University Farm to target this objective. Where soil was cultivated substantially wetter than field capacity, soil bulk density was increased and porosity decreased at cultivation depth compared with soil cultivated in a drier state. Penetration resistance was increased in soils cultivated whilst wet and differences increased as the soil dried, with resistances at 25 cm exceeding the limit for root penetration (3 MPa) in most seasons where the soil dried out through lack of rainfall and irrigation. Clod size distribution within the ridge was generally unaffected by most cultivation treatments, although allowing ploughed or cultivated soil to dry for several days prior to final roto-tilling produced cloddier ridges. Mean clod size decreased slightly during the season as the soil weathered but the rate of degradation was slow. The quantity of available soil water was generally unaffected by cultivation regime but rooting density was reduced in soils cultivated whilst wet by c. 15 %, with roots proliferating in the region above the cultivation interface as a consequence of being unable to penetrate the areas of greater soil resistance. Cultivating soil whilst wet also increased leaf and tuber water potential and stomatal resistance. Measured soil moisture deficits at 25 cm depth in soil cultivated wet were greater than when cultivated whilst dry, indicating a shallower zone of water uptake by crops grown in compacted soil.

Applying nitrogen fertilizer increased the rate of canopy development and persistence and radiation absorption potential more than applying irrigation but cultivating the soil whilst wet had relatively little overall effect on ground cover development and duration over the 3 years of the project. Averaged over the 3 years, tuber fresh weight yields in Maris Piper were increased by similar amounts by nitrogen and irrigation application (c. 12 t/ha) and by a much smaller amount by cultivating soil whilst dry compared with wet (c. 1.6 t/ha). The overall effects of soil compaction on yield were less than in a similar experiment in 2006 (10 t/ha) and only in one year out of three was the difference significant (c. 5 t/ha in 2008), so the effects of cultivation on yield appear to be variable despite similar practices at planting.

A survey of 47 commercial fields showed that within an individual field, the wetter a soil was when cultivating at planting, the greater the bulk density measured at cultivation depth. There were differences in the slopes of the relationship between bulk density and soil water content between fields and these slopes were negatively correlated with both the proportion of clay and silt and organic matter in the soil. However, for fields with similar soil texture and within fields with similar texture, there were large differences in the water content of the soil at 30 cm at planting, so the target of providing an optimum window for cultivation in terms of soil water content needs further work. Nevertheless, it is ultimately hoped that this information can help provide a useful set of recommendations for growers when cultivating fields in spring.
In irrigation experiments, maintaining the soil moisture deficit close to Field Capacity increased tuber yield as long as early over-watering was avoided. Any temporary restriction to irrigation was detrimental to yield. There was no evidence of differential drought tolerance or irrigation yield response amongst the cultivars selected. In the experiments in the UK, there were only slight differences between varieties in how stomatal resistance responded under contrasting irrigation treatments and these were not consistently large enough to point to real differences in stomatal function that may have affected water use efficiency. By contrast, in work conducted in Washington,

USA under higher evapotranspiration demand, there were significant varietal differences in stomatal resistance and leaf water potential that suggested differences in water use efficiency could be gained by optimising irrigation scheduling for different varieties. Irrigation generally had no significant effect on tuber dry matter concentration at final harvest even though the patterns of dry matter concentration during the season varied greatly between irrigation regimes. Where plots were over-watered for 3 weeks following tuber initiation, there was a significantly greater dry matter concentration compared to all other irrigation regimes and the effects were still apparent at the end of the season. There was a consistently greater dry matter concentration in tubers grown in soil cultivated wet compared with soil cultivated dry, indicating that water movement into tubers was compromised by poor water uptake from compacted soil. Control of common scab was generally better where soils were kept at Field Capacity following tuber initiation but the development of deep cracks in tubers was increased by early over-watering, indicating that caution is needed to avoid over-watering during the scab control period. In Vales Sovereign late over-watering increased the incidence and severity of superficial cracking centred on lenticels.

2. INTRODUCTION

Crop water supply is a function of soil water holding capacity and rooting density, both of which are influenced by soil structure and density. Cultivating soil at the optimal water content reduces compaction, cloddiness and the risk of soil slumping through structural degradation during the season. Significant improvements to yield and efficiency of use of soil water and irrigation could be made by understanding the parameters that define these soil conditions. Cloddy seedbeds are created when soil is initially cultivated whilst too wet and then left to dry for too long before a secondary cultivation takes place. Such seedbeds are difficult to wet uniformly for common scab control, which leads to over-watering and they present harvesting difficulties with respect to bruising and dirt tare. There is also much interest shown by growers over the importance of ridge shape and the degree of pressure exerted by covering shares, hoods or ridge formers on the rear of planters but data are scarce on the effects of these variables. Important areas where changes in ridge shape and consolidation can have an effect are rate and uniformity of emergence, water infiltration during both early and late irrigation events, common scab severity and greening and ease of harvesting.

Irrigation is often poorly-scheduled in the UK, resulting in both over- and under-watering and reduced tuber quality and yield. An improved understanding of how plants balance their water status in relation to evaporative demand under different soil conditions will improve the efficiency of water and irrigation usage. BPC Project R263 on tuber turgor and bruising showed that tubers can supply water to leaves during periods of high evaporative demand and that their re-hydration depends on both soil water status and evaporative demand. The flux of water into and out of tubers over short periods is exceedingly small compared with the amount of water evaporated from the leaf surface each day but is sufficient to cause significant changes in bruising potential and dry matter concentration, both of which seem largely uncontrollable by growers at present. An understanding of plant water status under different soil conditions would aid prediction of overall water use by the plant and establish a possible control mechanism for variation in tuber dry matter concentration. Additionally, work on common scab in the previous three seasons as part of the Defra-LINK programme showed that over-watering during the critical phase can induce severe tuber cracking, mainly as a consequence of excess tuber hydration status and weak restraining forces of an immature periderm.

The objectives of the Water Use Efficiency project were to:

a) Determine a more quantitative measure of soil conditions in a potato seedbed.
b) Determine the optimum soil water content for cultivation so that seedbed compaction is avoided and the tilth created is clod-free but structurally stable.
c) Determine how plants balance their water status in relation to evaporative demand under different soil conditions.
d) Establish a possible control mechanism for variation in tuber dry matter concentration by examining the relationship between plant and soil water status under varying evaporative demand.

This three-year project used a series of experiments and commercial crops to target these objectives.

3. Materials and Methods

Several experiments used common materials and methods and these are cross-referenced to the experiment where the method is first described. All experiments were conducted at Cambridge University Farm (CUF) unless indicated.

3.1. Experiment 2008

This experiment was performed in collaboration with the PCL Projects on Nitrogen Management (R405) and Tuber Number (R296) in order to utilize resources more effectively. The experiment tested all combinations of two cultivation regimes (Unsmeared, Smeared); three irrigation regimes (Unirrigated, Irrigated, Over-irrigated), two clod size distributions within the ridge (Cloddy, Fine) and two nitrogen (N) application rates (0, 200 kg N/ha). The experiment was a randomized split-plot design with four replicates containing cultivation, irrigation and cloddiness treatments allocated at random to mainplots and nitrogen fertilizer treatments allocated at random to sub-plots.

3.1.1. Cultivation, irrigation and cloddiness treatments

Details of the sequence of cultivations, irrigation and planting operations are given in Table 3. The average soil texture was a sandy loam but with coarser- and finer-textured areas within the experimental area. Stone content was slight to moderate. Where the intention was to create a fine tilth, the soil was rotavated shallowly soon after ploughing and some time before the main cultivation to reduce the clod size. To create wet soil for the main cultivation, half the plots were irrigated in the afternoon preceding cultivation. The water content of the soil at 20-25 cm depth was measured immediately post-irrigation using a Delta-T Devices Theta Probe ML-2. The Unsmeared plots had a soil water content of 30.1 ± 0.42 % and the Smeared plots 37.7 %. Following overnight drainage, the water content at cultivation depth was 30.2 ± 0.39% and 33.1 % for Unsmeared and Smeared, respectively. The main seedbed cultivation treatment was carried out using a rotavator with the lowest possible forward speed and with high rotor speed to allow the tines to spend as much time as possible working at the cultivation front. Ridging bodies were removed from the rotavator as experience in 2006 showed that wet soil tended to 'bulldoze' in front of the shares and produce a very inconsistent ridge shape. The flat profile remaining after the main cultivation was ridged within 2 hours.

Operation	Date
Plough @ 25–30 cm	2 April
Rotavate with Howard rotavator @ 10-15 cm (Fine plots only)	3 April
Irrigation (21.1 mm) on Smeared plots	24 April (12:35-17:00 h)
Rumpstad Rotoridger rotavator (ridging bodies removed) @ 25 cm	25 April (8:30-11:00 h)
Ridged with fixed-body Cousins ridger	25 April (12:00 h)
Planted and fertilizer applied	28 April
Re-ridged with fixed-body Cousins ridger	28 April

Table 1. Details of cultivation and irrigation operations around planting in Expt 2008

3.1.1.1. Irrigation

Overhead irrigation was applied through a boom (RST Irrigation) and hose reel (Perrot SA, SH63/280) combination. Plots were differentially irrigated by turning nozzles on or off along the length of the boom. Nozzles were spaced at c. 0.5 m, so individual plots could be irrigated. Where the randomisation of plots necessitated, the flow of water to the boom was turned off and the boom wound in using the tractor PTO shaft until the next strip of plots. Mean irrigation amounts were estimated from 32 rain gauge readings per irrigation treatment, situated at ground level and not shielded by foliage. Irrigation timings and amounts are shown in Table 2. The Unirrigated treatments received only rainfall whilst the Irrigated plots were targeted not to exceed 30 mm soil moisture deficit (SMD). The Over-irrigated plots had irrigation applied 2-4 days after a previous irrigation or closely following large rainfall events so that appreciable over-fill of the soil occurred.

	Irrigation treatment	
Date	**Irrigated**	**Over-irrigated**
19 June	18.7	18.7
26 June	21.6	21.6
1 July	21.6	21.6
3 July		29.9
18 July		30.1
25 July	24.4	24.4
29 July		30.4
1 August	17.9	17.9
4 August		30.0
14 August		30.2
29 August	21.5	21.5
Total	125.7	276.3

TABLE 2. IRRIGATION TIMINGS AND AMOUNTS (MM) FROM PLANTING TO FINAL HARVEST IN EXPT 2008

3.1.2. Crop planting, sampling and analysis

The experiment was planted by hand using Maris Piper (certification grade SE1; 25-35 mm; 2030 count/50 kg) into pre-formed ridges on 28 April. The ridges had 76 cm centres and the within-row spacing was 25 cm giving an intended plant population of 52 500/ha. Each plot was eight rows (6.1 m) wide and 8.0 m long for 200 N treatments and 4.5 m for 0 N. There was a 2 m gap between strips of plots to allow irrigation nozzles to be switched on or off between plots. The N treatments were applied as ammonium nitrate fertilizer immediately after planting as a single dressing. The fertilizer was then incorporated and the ridges reformed using a fixed-body Cousins ridger.

Plant emergence was measured every 3-5 days until complete and ground covers were measured weekly from 50 % plant emergence to final harvest using a grid (Burstall & Harris 1983). Crop samples to measure yield were taken on four occasions (24 June, 21 July, 26 August and 24 September). At each harvest, 10 plants (1.91 m2) were taken from rows two and three or six and seven of each eight-row plot. An unharvested discard area of at least two plants was left between adjacent harvest areas or plot ends. At each harvest, the number of plants and stems was recorded and all tubers > 10 mm were collected. The tubers were graded in 10 mm increments and the number and the fresh weight (FW) of tubers within each grade was recorded. For determination of tuber dry matter (DM) concentration, a sub-sample of tubers (c. 1 kg) was taken from the 50-60 mm size grade (or from a representative size grade at early harvests) and then washed, chipped and dried to constant weight in a fan-assisted oven at 90 °C using 90 % recirculated air. A sub-sample of 50 tubers from the final harvest was washed and assessed for common scab incidence and severity in the categories: 0, 0-1, 2-5, 6-25, 26-60 and 61-100 % surface area infected with scab. Tubers were also assessed for secondary growth defects at final harvest.

3.1.3. Soil moisture deficits and soil water content

Soil moisture deficits were estimated and irrigation treatments scheduled using the Cambridge University Farm Potato Irrigation Scheduling System model based on a modified Penman-Monteith evapotranspiration equation and using ground cover to adjust the crop coefficient values (Stalham & Allen 2004). Meteorological data were obtained from a Delta-T Devices weather station c. 200 m from the experiment. Soil water content was measured using a Delta-T Devices Theta Probe ML-2 in three replicate blocks of Fine cloddiness treatments. The probes were installed at emergence at two depths (25 and 50 cm) mid-way between two adjacent plants in row four or five and approximately 1 m from the end of the plot to avoid the changeover area between irrigation regimes. The probes were connected to a Delta-T Devices DL2 logger and readings were logged every 10 minutes. Owing to logger malfunction, most readings were lost between 5 and 16 June.

3.1.4. Soil properties

3.1.4.1. Textural analysis

A composite sample of soil (12 plots per sample) from the top 30 cm was taken from each replicate block of the experiment post ploughing on 3 April, dried for 24 h at 105 °C and sent to a commercial laboratory (NRM Ltd) for three-phase pipette textural determination. The sand fraction was dry sieved into fine (60-200), medium (200-600) and coarse (600-2000 μm) grades.

3.1.4.2. Bulk density and porosity

Dry bulk density was measured on 30 April-1 May, 5-6 June, 21-22 August and 29-30 September by inserting a stainless steel soil sampling ring (5 cm diameter x 5 cm depth) into the centre of the ridge and excavating soil carefully from around the ring using a small builder's trowel. The top 2-3 cm of soil at the ridge apex were removed before the ring was inserted. Where the ring could not be pushed into the soil using hand pressure on the back of the trowel, it was gently forced into the soil using a block of wood and hammer. Care was taken to ensure that the rim of the sampling ring was flush with the soil surface. The ring was sealed with a plastic lid, undercut with a knife and the trowel pushed underneath to extract the core. The outside of the ring was cleaned of excess soil and the sample was pushed into a plastic bag and sealed. The soil sample was weighed then dried for 24 h at 105 °C in a re-circulating oven. Following re-weighing, the sample was ground coarsely and the stones (> 2 mm) removed by sieving and weighed. From the measurements of dry bulk density, water content and stone content and standard estimates for particle and stone bulk density, it was possible to derive the total pore space (porosity) and air capacity of the soil core.

3.1.4.3. Resistance

Soil resistance readings were taken using an Eijkelkamp Penetrograph penetrometer (1 cm2 60° cone tip) in the centre of the ridge to a depth of 50 cm on four occasions: 29 April and 5 June and after dry periods on 4 July and 24 July. Six replicate readings of resistance were taken in each plot. A Pesola 80098 mini-penetrometer was used to measure ridge strength on 5 June and 4 July. Six replicate readings of resistance were taken in each plot by inserting the tip of the penetrometer in a horizontal direction from the base of the furrow into the centre of the ridge and recording the maximum resistance. Prior to each set of mini-penetrometer readings, a measurement of soil water content was made using a portable Theta Probe in six locations close to where the penetrometer readings were taken.

3.1.4.4. Water holding capacity

Soil water holding capacity was determined using a pressure membrane apparatus at a commercial laboratory (NRM Ltd). Duplicate cores (5 cm diameter x 5 cm depth) were taken using stainless steel sampling rings from 15-20 and 25-30 cm depths during bulk density sampling on 5 June. The soil samples were sealed at both ends with plastic lids, further sealed inside plastic bags and delivered in their original sampling rings to the laboratory. The water content of the samples at 60 kPa (very easily available) and 200 kPa (easily available) pressure was calculated.

3.1.4.5. Ped size distribution

Ped size distribution was measured by grading a medium- (0.91 l) and a large-volume (3.30 l) soil sample on four occasions (25 April, 29 April, 19 June and 29-30 September). For the large-volume sample, 2-3 cm of soil was removed from the apex of the ridge and a handled aluminium soil sampling ring (20.5 cm internal diameter x 10 cm depth) was pushed into the centre of the ridge mid-way between two plants and extracted by sliding a flat spade underneath. The soil was transferred to a plastic bag which was then weighed and sealed. At a subsequent date, the soil sample was sieved into ten grades (< 2, 2-6, 6-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40 and 40-45 mm) using a combination of potato riddle grids and soil sieves (Endacott). The soil in each grade was weighed and the weight fractions in each grade calculated. The medium-volume sample was taken to 20 cm depth in the same manner but the sampling tool was made from aluminium pipe with 7.6 cm internal diameter. The soil was transferred to a plastic bag which was then weighed and sealed. The sample was carefully tipped into aluminium trays and dried at 105 °C for 48 hours, then reweighed and sieved into ten grades (< 2, 2-6, 6-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40 and 40-45 mm). Stones >=2 mm diameter were removed from each sample after dry-sieving and weighed separately. An additional measurement of dry bulk density was calculated from the medium-volume samples.

3.1.5. Leaf and tuber water potential

Measurement of tuber and leaf water potential (WP) were made using a Skye Instruments SKPM1400 pressure chamber. All measurements took place in the field so that minimal time elapsed between harvest and measurement. A single leaf in the upper canopy that was fully exposed to sunlight was measured on four plants in each plot. The leaf was excised at the base of the petiole using a pair of scissors. These four plants were then dug carefully by hand so that tubers remained attached to their stolons. Tubers for water potential were selected by size (40-70 mm) and for integrity of the attached stolon. Tubers attached to damaged, collapsed, senesced, short (< 30 mm), very thin (< 1 mm) or thick (> 4 mm) stolons were not used for water potential but were used for tuber dry matter assessment. Immediately prior to inserting in the pressure chamber, the petiole or stolon was trimmed using a sharp scalpel. A total of four tubers per plot were measured for WP.

3.1.6. Stomatal resistance

Stomatal resistance (SR) is the resistance to loss of water vapour through the stomata. Stomatal resistance was measured using a Delta-T Devices AP4-UM-3 Porometer fitted with a slotted cup. The porometer works by measuring the time it takes for a leaf to release sufficient water vapour to change the relative humidity in a small chamber by a fixed amount. This is compared with a calibration plate of known resistance in order to derive the SR of the leaf. An increased resistance indicates that the average stomatal aperture within the leaf chamber is reduced in size. Calibrations were performed before each set of measurements if the ambient air relative humidity was more than 5 % different from the previous set of readings or when changing the relative humidity set point. The calibration equations were re-performed if the error in curve-fitting was > 10 %, with the target being 5 % if sufficient time was available for the calibration process. A single leaf that was fully exposed to sunlight was measured on four random plants in each plot. The plants were reached by leaning over guard plants in the plot. Readings were allowed to stabilise and then recorded when < 2 % different from the previous reading.

3.1.7. Rooting density

Root length density (RLD, cm root/cm3 soil) was estimated on 8 July and 21 August by taking two soil cores (5 cm diameter x 5 cm depth) from each plot using the same stainless steel sampling rings as for bulk density measurements. The two cores were taken from two symmetrical positions within the ridge, one half-way between the centre of the ridge and the left-hand edge of the ridge at the other on the right-hand side. The samples were taken at three depths (20-25, 25-30 and 30-35 cm) corresponding to the main cultivation depth. Soil cores were transferred to plastic bags before being stored at 2 °C until washing. The soil cores were washed out over a series of diminishing mesh soil sieves (2, 0.6, 0.2 mm) to collect the roots. Roots were floated off and washed into a plastic tray or collected from the meshes using tweezers. Newman's (1966) grid intersection technique as modified by Marsh (1971) and Tennant (1975) was used to estimate total root length per sample. A 0.5 x 0.5 cm grid of graph paper was attached to a shallow transparent tray of dimensions 17 x 11 cm and the extracted roots floated in a minimal quantity of water to prevent movement in the tray. Dead, brown root material of potato origin was included in length determinations but owing to the fragility of these older roots, recovery on extraction from the soil was inherently low.

3.2. Experiment 2009a

The experiment was conducted at CUF and examined all combinations of four soil water contents at cultivation (Moist, Field Capacity, Wet and Over-wet); two irrigation regimes (Unirrigated and Irrigated) and two dates of planting (15 and 29 April). The experiment was a randomized block design with three replicates.

3.2.1. Cultivation, irrigation and date of planting treatments

Details of the sequence of cultivations, irrigation and planting operations are given in Table 3. The average soil texture was a sandy clay loam but with coarser- (sandy loam) and finer- (clay loam) textured areas within the experiment. Stone content was slight (c.5 %). To create wet soil for the main cultivation, all plots except the Moist cultivation treatment were irrigated just prior to cultivation. The water content of the soil at 25 cm depth was measured immediately post-irrigation using a Delta-T Devices Theta Probe ML-2 and HH2 meter and then every 3-12 hours as the soil initially drained of excess water and then dried through evaporation. The intention was to cultivate at 26, 29, 32 and 36 % water content for the Moist, Field Capacity, Wet and Over-wet treatments, respectively, but the actual water contents were as detailed in Table 4. At the earliest planting, 18.8 mm of irrigation increased the soil water content at 25 cm from 26.9 % to 36.1 %, whereas it only increased it from 26.5 % to 33.9 % at the later planting owing to the topsoil being drier (Table 4). The cultivation treatment was carried out using a Howard rotavator operating at the slowest possible forward speed and with high rotor speed to allow the tines to spend as much time as possible working at the cultivation front. The flat profile remaining after rotavating was ridged using a Cousins fixed-body ridger for planting when the last cultivation treatment had been completed.

		Planting date	
Operation	**Plots treated**	**15 April**	**29 April**
Plough at 25-30 cm	All	3 March	3 March
Spring tine at 10-15 cm	All	6 April	6 April
Irrigation (18.8 mm)	Field Capacity, Wet, Over-wet	7 April (13:00-15:40h)	27 April (12:00-15:00h)
Rotavate at 20-25 cm	Moist	7 April (11:00h)	27 April (9:00 h)
	Field Capacity	8 April (16:20h)	29 April (10:00h)
	Wet	8 April (10:00h)	28 April (11:00h)
	Over-wet	7 April (16:00h)	27 April (16:00h)
Ridged	All plots	9 April (14:00h)	29 April (12:00h)
Planted	All plots	15 April (8:30h)	29 April (14:00h)
Re-ridged	All plots	15 April (14:00h)	29 April (16:00h)

TABLE 3. DETAILS OF CULTIVATION AND IRRIGATION OPERATIONS IN EXPT 2009A

		Moisture content at operation	
Operation	**Treatment**	**15 April**	**29 April**
Plough	All	32.9 ± 0.29	32.9 ± 0.29
Pre-irrigation	All	26.9 ± 1.42	26.5 ± 1.61
Post irrigation	Field Capacity, Wet, Over-wet	36.1 ± 0.79	33.9 ± 0.90
Rotavate	Moist	26.9 ± 1.42	26.5 ± 1.61
	Field Capacity	29.6 ± 1.63	28.6 ± 1.21
	Wet	32.2 ± 1.15	32.0 ± 0.50
	Over-wet	36.2 ± 1.21	34.7 ± 0.90

TABLE 4. SOIL WATER CONTENT (% VOLUMETRIC) AT 25 CM DEPTH AT VARIOUS OPERATIONS IN EXPT 2009A

3.2.2. Irrigation

Overhead irrigation was applied through a boom and hose reel as in Expt 2008. Unirrigated treatments received only rainfall whilst the Irrigated plots were targeted not to exceed 25 mm soil moisture deficit using the CUF Potato Irrigation Scheduling model. Nine applications (20.3-25.8 mm) totalling 223 mm were made on 3, 19 and 26 June, 3 and 14 July, 17 and 25 August and 7 and 17 September.

3.2.3. Crop planting, sampling and analysis

The experiment was planted by hand with Maris Piper (certification grade E1; 35-40 mm; mean weight 40 g) into pre-formed ridges on the dates shown in Table 3. The ridges had 76 cm centres and the within-row spacing was 30 cm giving an intended plant population of 43 700/ha. Each plot was four rows (3.0 m) wide and 12 m long. There was a 5 m gap between strips of plots to allow tractors to turn and irrigation nozzles to be switched on or off between plots. Following planting, the ridges were re-built using a Cousins fixed-body ridger. A solution of concentrated (34.6 % vol.) ammonium nitrate fertilizer (180 kg N/ha) was applied using a tractor sprayer on 30 April.

Plant emergence in the two central harvest rows was measured every 1-4 days until complete and ground covers were measured weekly from 50 % plant emergence to final harvest in two positions within each plot. Crop samples to measure yield were taken on four occasions. The initial sample was on 19 June for 15 April planting and 23 June for 29 April planting and subsequent harvests for both plantings were on 17 July, 6 August and 28 September. At each harvest, eight plants (1.83 m2) were taken from the two central harvest rows of each plot. An unharvested discard area of at least two plants was left between adjacent harvest areas or plot ends. At each harvest, the number of plants and stems was recorded and all tubers > 10 mm were collected. The tubers were graded in 10 mm increments and the number and the fresh weight (FW) of tubers within each grade was recorded. For determination of tuber dry matter (DM) concentration, a sub-sample of tubers (c. 0.6-1.0 kg) was taken from the 50-60 mm size grade (or from a representative size grade at early harvests) and then washed, chipped and dried to constant weight in a fan-assisted oven at 90 °C using 90 % re-circulated air. Fresh weights of entire haulm samples were weighed and a sub-sample of c. 1 kg taken to be oven dried.

3.2.4. Soil properties

3.2.4.1. Textural analysis

A composite sample of soil (16 plots per sample) from the top 30 cm was taken from each replicate block of the experiment post planting, dried for 24 h at 105 °C and sent to a commercial laboratory (NRM Ltd) for three-phase pipette textural determination. The sand fraction was sieved into fine (60-200), medium (200-600) and coarse (600-2000 µm) grades.

3.2.4.2. Bulk density and porosity

Dry bulk density was measured on 14-18 May and 7-10 August as in Expt 2008.

3.2.4.3. Resistance

Soil resistance readings were taken using an Eijkelkamp Penetrograph penetrometer (1 cm2 60° cone tip) in the centre of the ridge to a depth of 50 cm on four occasions: 16 or 30 April (the day after each respective planting), 8 June and after a dry period on 3 July. Six replicate readings of resistance were taken in each plot.

3.2.4.4. Water holding capacity

Soil water holding capacity was determined as in Expt 2008.

3.2.4.5. Soil water content

Soil water content was measured at 15 minute intervals using a Delta-T Devices Theta Probe ML2 permanently installed at emergence in the centre of the ridge mid-way between two adjacent plants at a depth of 15 cm and logged using a Delta-T Devices DL2 logger. Two replicates of all plots of the Moist and Over-wet cultivation treatments were monitored for soil water content.

3.2.4.6. Ped size distribution

Ped size distribution was measured by grading a large-volume (2.0 l) soil sample taken on 19 June using a box section aluminium sampler (20 x 10 x 10 cm, width x length x depth) as in Expt 2008. An additional measurement of dry bulk density within the ridge was calculated from these large-volume samples.

3.2.5. Plant measurements

Stomatal resistance was measured as detailed in Expt 2008. Unless readings were taken on more than one occasion each day, the time of measurement was c. 15:00 h (readings commenced at 14:30 and finished at 15:30 h). On three days during the season (23 and 30 June and 16 July), stomatal resistance assessments were taken every 2 hours throughout the day to determine whether crops exhibited reduced stomatal aperture (i.e. increased resistance) under high temperatures during mid-afternoon as a consequence of water stress created by lack of irrigation, soil compaction or leaf age. On these days, the first set of readings took place at 08:00 h.
Measurements of leaf and tuber water potential during the periods of over-watering were made using a Skye Instruments SKPM1400 pressure chamber as detailed in Expt 2008. A total of four leaves or tubers per plot were measured for water potential. Unless readings were taken on more than one occasion each day, the time of measurement was c. 15:00 h (readings commenced at 14:00 and finished at 16:00 h). Owing to the time required in sampling, only Moist and Over-wet treatments were sampled when water potential was measured every 2 hours during the day. These frequent measurements began at 08:30 h and took c. 60-75 minutes to complete each set. Root length density (RLD, cm root/cm3 soil) was estimated on 7-10 August by taking two replicate soil cores as detailed in Expt 2008.

3.3. Experiment 2009b

The experiment was a randomized block design with three replicates. Treatments consisted of all combinations of five irrigation regimes (rainfed only, I-; irrigated at 20 mm SMD throughout, I; unirrigated for 2 weeks between 4 and 6 weeks post-tuber initiation otherwise as I, I- 4-6; over-irrigated from tuber initiation for 3 weeks otherwise as I, I+ 0-3; over-irrigated between 10 and 13 weeks post-tuber initiation otherwise as I, I+ 10-13) and three varieties (Hermes; Maris Piper; Vales Sovereign). There were three replicate blocks.

The experiment was planted on 14 April 2009 using 35-40 mm Maris Piper SE 1, 35-40 mm Vales Sovereign SE2 and 40-45 mm Hermes E1 seed at a within-row spacing of 25 cm and 12 cm deep into pre-formed ridges, which were raked after planting to re-form the original ridge. Plots were 8 m long and eight rows (6.10 m) or four rows (I+ 10-13) wide. Ammonium nitrate was applied at a rate of 180 kg N/ha post-planting as a concentrated liquid solution.

3.3.1. Irrigation

Irrigation was scheduled using the CUF Potato Irrigation Scheduling Model. The irrigation was timed based on the mean soil moisture deficits in the I treatments of Maris Piper and Vales Sovereign as there was little difference in emergence between these two varieties. Mini-sprinklers (Dan Modular Small Swivel Yellow Anti-mist nozzles) were used to provide additional irrigation for I+ 0-3 and I+ 10-13 treatments. Sprinklers on 1 m risers were installed in every alternate furrow at 1 m spacing to form a grid pattern in the plot. They were adjusted to run at very low pressure (c. 0.55 bar) to reduce the risk of misting and drift into adjacent plots. The sprinkler systems were calibrated at the beginning of the season to determine application rates in mm/hour at 0.55 bar pressure in each plot. The mean application rate was 20 mm/hour. Irrigation for over-irrigated plots was twice daily (07:00 and 19:00 h) with a total of 5 mm/day, to ensure that plots were kept at, or above, Field Capacity. Irrigation amounts applied are detailed in Table 5. Unlike the main boom irrigation applications, the timings of the over-watered periods were based on the exact dates of tuber initiation for each variety rather than a mean of all varieties, with the respective sprinklers turned off or on accordingly.

	Irrigation regime				
Date	**I-**	**I**	**I- 4-6**	**I+ 0-3**	**I+ 10-13**
Rainfall	227.0	227.0	227.0	227.0	227.0
2 June		21.1	21.1	21.1	21.1
2-22 June				105.0	
19 June		21.2	21.2	21.2	21.2
25 June		23.2	23.2	23.2	23.2
3 July		24.2		24.2	24.2
13 July		24.2		24.2	24.2
10-30 August					105.0
17 August		24.2	24.2	24.2	24.2
25 August		24.2	24.2	24.2	24.2
Total	227.0	389.3	340.9	494.3	494.3

TABLE 5. TOTAL RAINFALL AND IRRIGATION (MM) APPLIED DURING THE SEASON FROM EMERGENCE TO FINAL HARVEST IN EXPT 2009B

In each plot of one replicate block, soil water content was measured at 15 minute intervals using a Delta-T Devices Theta Probe ML2 permanently installed at emergence in the centre of the ridge mid-way between two adjacent plants at a depth of 15 cm and logged using a Delta-T Devices DL2 logger.

Plant emergence was recorded every 1-2 days in each plot by counting the number of plants emerged in two harvest rows. Tuber initiation was determined by digging two plants per plot every 2 days from 10 days after 50 % plant emergence and recording a plant as having initiated tubers if one or more stolons had swollen to twice their diameter at the tip.

A final harvest of 12 plants was taken on 9 September. An unharvested discard area of at least two plants was left between adjacent harvest areas or plot ends. The number of plants and stems was recorded and all tubers > 10 mm were collected. The tubers were graded in 10 mm increments and the number and the fresh weight of tubers within each grade was recorded

3.3.2. Common scab and tuber defects

Following grading, tubers were assessed for incidence and severity of common scab in the categories: 0, 0-1, 2-5, 6-25, 26-60 and 61-100 % surface area infected with scab. Tubers were also assessed for type, incidence and severity of tuber cracking at final harvest. The cracks were divided into two types: (a) 3-8 mm deep linear cracks traversing either along the longitudinal axis or from the apical end and (b) superficial (1-3 mm deep) cracks emanating from foci centred on lenticels. These superficial cracks covered a large surface area where there was high incidence of cracking on an individual tuber.

3.4. Experiment 2009c

The experiment was conducted at Heygate Farms, Cockley Cley, Norfolk on a sand soil (Newmarket 1 Association) with a high flint content (20-35 %), particularly at 30-35 cm depth, which necessitates destoning to avoid severe damage to tubers at harvest. The experiment was redesigned on site when it was found that the soil was too dry and sandy to create any significant compaction through destoning deeper than normal. It was decided instead to introduce a soil profile treatment into the experiment.

The experiment was machine-planted on 7 May using a Grimme GL32B planter with auto depth control via ultra-sonic sensor. Rooster seed (35-45 mm) was planted at a target spacing of 41 cm. The shaping hood was changed from rows to beds, according to treatment by removing the central divider, which left a flat bed profile compared with the traditional two trapezoidal-shaped rows within the bed. The hydraulic pressure exerting on the covering hood was adjusted from the tractor cab.
Treatments consisted of two depths of destoning (Shallow, 20-25 cm; Deep, 35 cm), two bed profiles (Ridge, Bed) and two consolidation pressures exerted by the covering hood (Minimum, 0 % on planter meter; Maximum, 85 %). All combinations of these treatments were arranged randomly in three replicate blocks. Plots were two beds (3.66 m) wide and 20 m long. To avoid start and stop edge effects of machinery, a 5 m length of both beds was marked out in the middle of each plot where measurements were taken. The experiment was harvested on 1 October by hand digging 2 m of the middle two rows in each plot.

Planting depth was measured immediately post-planting by uncovering five seed tubers and measuring the soil coverage to the top of the ridge or bed. Soil bulk density of the top 10 cm of ridge or bed was measured just prior to emergence and again at final harvest using a box section aluminium sampler (20 x 10 x 10 cm, width x length x depth). Emergence was measured by counting the number of plants emerged in a 5 m length of two rows of adjacent beds. On 22 May, soil resistance was measured mid-way between two plants in two positions in each row of the plot using an Eijkelkamp Penetrograph (1 cm2 60° cone tip) to a depth of 40 cm, where a band of stones prevented further penetration.

Irrigation was carried out using a Briggs VR6 110/530 hosereel running at 7.4 bar with an offset wheeled gun trolley and adjustable angle gun. A 22 or 24 mm nozzle was used for 18 or 25 mm applications, respectively, and the retraction speed altered to change the application rate. Water infiltration into the ridge/bed following irrigation was measured on two occasions, on 12 June and 14 July. Soil water content was measured at a depth of 14 cm using a Delta-T Theta Probe ML2 and HH2 meter. Thirty minutes prior to irrigation, the probe was inserted between two adjacent plants in the centre of each row of the two beds and in each unwheeled furrow in the centre of each bed and measurements of volumetric soil water content taken. Approximately 3 hours after irrigation commenced, a second set of readings was taken to measure the change in soil water content.

3.5. Experiment 2010a

The experiment examined all combinations two primary cultivation techniques (Plough and Non-plough), two dates of cultivation (Early and Late), two varieties (Lady Rosetta and Maris Piper) and two rates of N fertilizer (0 and 180 kg N/ha). The experiment was a split-plot design with cultivation treatments as main-plots and variety and N-rate allocated to sub-plots with three replicates.

3.5.1. Cultivation, irrigation and date of planting treatments

Details of the sequence of cultivation and planting operations are given in Table 3. The average soil texture was a clay loam but with lower clay content in the middle of the experimental area than at either end. Stone content was moderate (mean 12 %). The water content of the soil at 25 cm depth was measured immediately prior to each cultivation operation by digging a pit with a spade and using a Delta-T Devices Theta Probe ML-2 and HH2 meter. Six replicate readings were taken in different locations within each plot.

	Cultivation			
Operation	**Plough Early**	**Non-plough Early**	**Plough Late**	**Non-plough Late**
Simba SLD @ 30 cm	4 September	4 September	4 September	4 September
Plough @ 30 cm	16 March		6 April	
Keeble Progressive @ 15 cm				6 April
Keeble Progressive @ 20 cm				8 April
Keeble Progressive @ 30 cm				13 April
Rumptstad Rototiller @ 25 cm	16 March	16 March	14 April	14 April
Re-ridge (Cousins)	14 April	14 April	14 April	14 April
Plant	19 April	19 April	19 April	19 April

TABLE 6. DETAILS OF CULTIVATION AND IRRIGATION OPERATIONS IN EXPT 2010A

Overhead irrigation was applied through a boom and hose reel combination as in Expt 2008. Plots were targeted not to exceed 30 mm soil moisture deficit (SMD) using the CUF Potato Irrigation Scheduling model. Nine applications (17-26 mm) totalling 206 mm were made on 28 May, 18, 21 and 30 June, 7, 13, 19, 23 and 30 July. No irrigation was required in August and September.

3.5.2. Crop planting, sampling and analysis

The experiment was planted by hand using Maris Piper (certification grade E1; 25-30 mm; mean weight 21 g) and Lady Rosetta (grade SE2; 35-40 mm; mean weight 36 g) seed into pre-formed ridges. The ridges had 76 cm centres and the within-row spacing was 25 cm giving an intended plant population of 52 500/ha. Each plot was four rows (3.0 m) wide and 12 m long and was planted at right angles to the normal row direction in the field so that the cultivation treatments could be carried out effectively. No fertilizer other than nitrogen for N treatments was applied as soil indices for P, K & Mg were high (4, 2+, 2, respectively).

Plant emergence in the two central harvest rows was measured every 1-4 days until complete and ground covers were measured weekly from 50 % plant emergence to final harvest in two positions within each plot using a grid. Crop samples to measure yield and nitrogen uptake were taken on four occasions, 18 June, 22 July, 23 August and 27 September. At each harvest, 12 plants (2.29 m2) were taken from the two central harvest rows of each plot. An unharvested discard area of at least two plants was left between adjacent harvest areas or plot ends. At each harvest, the number of plants and stems was recorded and all tubers > 10 mm were collected. The tubers were graded in 10 mm increments and the number and the fresh weight (FW) of tubers within each grade was recorded. For determination of tuber dry matter (DM) concentration, a sub-sample of tubers (c. 1 kg) was taken from the 50-60 mm size grade (or from a representative size grade at early harvests) and then washed, chipped and dried to constant weight in a fan-assisted oven at 90 °C using 90 % recirculated air. Fresh weights of entire haulm samples were weighed and a sub-sample of c. 1 kg taken to be oven dried. Nitrogen concentrations in dried haulm and tuber samples were determined at a commercial laboratory (NRM Ltd, Bracknell).

3.5.3. Soil properties

Dry bulk density in 5 cm increments throughout the profile was measured on 12-13 August using the method detailed in Expt 2008. The bulk density and the distribution of different size peds within the ridge were determined on two occasions, 28 May and 28 September. An additional ridge bulk density measurement was made on 12-13 August at the same time as the small cores were taken but ped size distribution was not measured on these samples. After excavating the top 2 cm of soil from the ridge, a steel soil sampling box (20 cm wide × 10 cm long× 10 cm depth) was pushed into the centre of the ridge between two plants with the widest dimension across the ridge to a depth of 10 cm. A lid was then placed on the box, undercut with a builder's trowel, a flat steel plate pushed underneath the box and the box and soil lifted out.

The soil core was transferred to a plastic bag before being weighed and then dried for 24 h at 105 °C in a re-circulating oven. Care was taken when handling bags of soil to avoid damaging the peds. The dried samples were then graded using a series of sieves into > 45, 45-40, 40-35, 35-30, 30-25, 25-20, 20-15, 15-10, 10-6, 6-2 and < 2 mm fractions and the weight in each grade determined.

Soil resistance readings were taken using an Eijkelkamp Penetrograph penetrometer in the centre of the ridge to a depth of 50 cm on three occasions: 19 April, 8 June and after a dry period on 23 July. Four replicate readings of resistance were taken in each plot.

Soil water holding capacity was determined using a pressure membrane apparatus at a commercial laboratory (NRM Ltd, Bracknell). A single core (5 cm diameter × 5 cm depth) was taken using stainless steel sampling rings from 25-30 cm depth on 28 May from Maris Piper, 180N treatments only. The soil samples were sealed at both ends with plastic lids, further sealed inside plastic bags and delivered in their original sampling rings to the laboratory. The water content of the samples at 60 kPa (very easily available) pressure was calculated on a gravimetric basis and converted to a volumetric reading by multiplying by the bulk density.

3.5.4. Plant measurements

Stomatal resistance was measured as detailed in Expt 2008. Root length density (RLD, cm root/cm3 soil) was estimated on 17 August by taking a block of soil (20 cm wide × 10 cm long× 10 cm depth) from each plot using a steel coring box. The ridge was excavated to the depth of the furrow (20 cm) to produce a flat surface. The box was then hammered into the centre of the ridge with the widest dimension across the ridge to a depth of 10 cm. A lid was then placed on the box, undercut with a builder's trowel, a flat steel plate pushed underneath the box and the box and soil lifted out. The soil core was transferred to a plastic bag before being stored at 2 °C until washing. The core was subsampled to c. 250 g fresh weight and then washed out over a series of diminishing mesh soil sieves (2, 0.63, 0.2 mm) to collect the roots. Roots, including dead, brown ones, were floated off and washed into a plastic tray or collected from the meshes using tweezers. The entire root sample from each sub-sample was then dried at 90 °C for 24 h and weighed. The dry weight of roots (RDW, g) was converted to length (RL, m) using the relationship derived by Stalham & Allen (2001):

RL=97.84 x RDW

3.6. Experiment 2010b

The experiment was a fully-randomized factorial design, with all combinations of two varieties (Maris Piper; Vales Sovereign) and six irrigation regimes, with three replicate blocks. The six irrigation regimes were rainfed only (Unirr); irrigated back to Field Capacity overnight (0); irrigated whenever the soil moisture deficit (SMD) reached 10, 20, 30 or 40 mm (10, 20, 30, 40, respectively). Sufficient water was applied at each irrigation event to bring the soil back to Field Capacity, i.e. 10 mm at 10 mm SMD etc. The experiment was conducted on a sandy clay loam soil (56 % sand, 23 % silt and 20 % clay) with 12 % stone and 3.5 % organic matter content and pH of 7.2. The experiment was planted on 15 April 2010 using 25-30 mm Maris Piper SE 1 and 25-35 mm Vales Sovereign SE2 seed at a within-row spacing of 25 cm in 76 cm rows. The seed was dibbed 12 cm deep into pre-formed ridges, which were raked after planting to re-form the original ridge. Plots were 7 m long and four rows wide. There were two extra guard rows and a 2 m gap between plots to avoid irrigation drift from adjacent treatments. A concentrated (34.2 % vol.) solution of ammonium nitrate was applied at a rate of 180 kg N/ha post-planting.

Irrigation was scheduled using the CUF Potato Irrigation Scheduling Model. The different irrigation treatments were timed based on the mean SMDs of Maris Piper and Vales Sovereign as there was only one day difference in emergence between these two varieties. The same mini sprinkler system and layout was used as in Expt 2009a. Irrigation for 0 SMD treatments was timed to start automatically at 07:00 h, and the application rate adjusted between 3 and 6 mm/day according to evapotranspiration demand, to ensure that plots were returned to Field Capacity. Other irrigation treatments were watered between 8 and 11:00 h. Irrigation commenced in 0 and 10 mm SMD treatments 2 days prior to the onset of tuber initiation to ensure that the respective trigger SMDs were reached at initiation. Other irrigation timings received their first irrigation when the trigger SMD was reached after tuber initiation. Irrigation amounts applied are detailed in Table 7.

	Irrigation regime					
Date	**Unirr**	**0**	**10**	**20**	**30**	**40**
Rainfall	213	213	213	213	213	213
Irrigation	0	416	279	240	180	120
Drainage	29	239	112	90	64	56
Irrigation-drainage	-	177	166	150	116	64

TABLE 7. TOTAL RAINFALL AND IRRIGATION (MM) APPLIED DURING THE SEASON FROM EMERGENCE TO FINAL HARVEST IN EXPT 2010B

In each plot of two replicate blocks, soil water content was measured at 10 minute intervals using a Delta-T Devices Theta Probe ML2 permanently installed at emergence in the centre of the ridge mid-way between two adjacent plants at a depth of 15 cm and logged using a Delta-T Devices DL2 logger.

Plant emergence was recorded every 1-2 days in each plot by counting the number of plants emerged in two harvest rows. Tuber initiation was determined by digging two plants per plot every day from 13 days after 50 % plant emergence and recording a plant as having initiated tubers if one or more stolons had swollen to twice their diameter at the tip. Ground cover was measured weekly after emergence until final harvest using a grid in two positions in each plot.

A final harvest of 12 plants was taken on 21 September. The tubers were washed and then graded, counted and weighed in 10 mm increments. A representative sample of tubers weighing c. 500 g was dried at 90 °C for 48 h to measure tuber dry matter concentration. All remaining tubers were assessed for incidence and severity of common scab in categories of 0, 0-1, 2-5, 6-10, 11-25, 26-50, 51-75 and 76-100 % surface area (SA) infected with scab. Tubers were also assessed for type, incidence and severity of tuber cracking and growth defects at final harvest. The cracks were divided into two types: (a) 3-8 mm deep linear cracks traversing either along the longitudinal axis or from the apical end and (b) superficial (1-3 mm deep) cracks emanating from a focus centred on a lenticel and usually with 2-4 cracks arising from the same point. The superficial cracks covered a large surface area where there was high incidence of cracking on an individual tuber. The area of the tuber covered by superficial cracks was scored in categories of 0, 0-1, 2-5, 6-10, 11-25, 26-50, 51-75 and 76-100 % surface area affected.

3.7. Experiment 2010c

An irrigation experiment was conducted at the Othello Field Station, Washington State University (WSU), USA to provide data to increase understanding of water use under high evaporative demand. The experiment was a split-plot design with three replicate blocks. Three irrigation regimes comprised main-plots, with three varieties (Alturas, Russet Norkotah, Umatilla Russet) as sub-plots. The three irrigation regimes were (i) irrigated according to a schedule similar to that used by WSU on their experiments, to maintain the soil moisture deficit (SMD) < 10 mm including occasional over-watering events (WSU), (ii) irrigated according to a schedule set by CUF to maintain the SMD between 10 and 20 mm during June-August (CUF) and (iii) as (ii) but with temporary drought periods at the end of June (during a visit for crop measurements), in late-July and late-August to allow the SMD to increase to 30 mm (Drought). During September, irrigation was infrequent which allowed the SMDs to increase above the targets.

The soil was a Shano silt loam (18 % sand, 75 % silt and 7 % clay) and the experiment was planted by machine on 16 April at a within-row spacing of 25 cm and a depth of 15 cm. Plots were 4.6 m long and four rows wide. There was a 1.5 m gap between main-plots to avoid effects of irrigation drift. A basal dressing of 17 N, 90 P2O5, 112 K20 kg/ha was applied pre-planting and additional nitrogen totalling 152 kg/ha was applied via fertigation on 8, 16, 25 June and 7 July based on leaf petiole tests during the season according to the guidelines given by Lang et al. (1999). Irrigation was scheduled using the CUF Potato Irrigation Scheduling Model based on meteorological data obtained from the WSU Othello weather station c. 300 m from the experiment. The different irrigation treatments were timed based on the SMDs for Alturas. Irrigation was mainly applied via linear-move irrigator but differential treatments were applied using a trailed sprayer with flood nozzles. In mid-August, the SMD was allowed to increase progressively in the Alturas and Umatilla Russet plots to c. 50 mm at defoliation to avoid over-watering the Russet Norkotah plots which began senescing in mid-August. Irrigation amounts applied are detailed in Table 8. A summary of the weather data is presented in Table 9.

	Irrigation regime		
	WSU	**CUF**	**Drought**
Rainfall	80	80	80
Irrigation	547	441	409
Drainage†	97	36	28
Irrigation-drainage†	450	405	381
21 June	12.7	0	0
22 June	0	12.7	0
23 June	12.7	0	0
24 June	22.4	22.4	22.4
25 June	0	0	0

† Calculated for Alturas

TABLE 8. TOTAL RAINFALL AND IRRIGATION (MM) APPLIED DURING THE SEASON FROM EMERGENCE TO DEFOLIATION AND ON EACH OF THE DAYS DURING THE MEASUREMENT PERIOD, 21-25 JUNE IN EXPT 2010C

	Tmean	Tmax	ETmean	Rain
June	16.7	23.4	4.84	35
July	21.3	29.2	6.04	13
August	20.1	28.0	5.25	3
21 June	15.3	22.2	3.46	0
22 June	18.8	26.5	5.38	0
23 June	21.2	27.7	4.78	0
24 June	20.9	28.6	5.51	0
25 June	20.6	27.8	5.63	0

TABLE 9. AVERAGE MEAN (TMEAN) AND MAXIMUM (TMAX) TEMPERATURES (°C), MEAN EVAPOTRANSPIRATION (ETMEAN, MM/DAY) AND RAINFALL TOTAL (MM) DURING JUNE-AUGUST AND IN THE MEASUREMENT PERIOD IN EXPT 2010C

Measurements of stomatal resistance and leaf water potential were made between 21-25 June. Stomatal resistance was measured using a Delta-T Devices AP4-UM-3 Porometer fitted with a slotted cup as in Expt 2008. For the period of 5 days, 21-25 June, three or four sets of resistance readings were taken each day every c. 2.5 hours from c. 09:00 h to 16:00 h to determine whether crops exhibited reduced stomatal aperture (i.e. increased resistance) under high temperatures during mid-afternoon as a consequence of water stress created by the differential irrigation regimes.

Measurements of leaf water potential during the period 21-25 June were made with a PMS Instrument Company Model 615 Pressure Chamber using compressed air or nitrogen. A single leaf in the upper canopy that was fully exposed to sunlight was measured on four plants within harvest rows in each plot. Each leaf was excised at the base of the petiole using a pair of scissors and the petiole was trimmed using a scalpel immediately prior to inserting in the chamber. Two readings were taken per leaf. The chamber was sited on a tractor parked close to the experiment. Leaves were placed in a plastic bag in the shade after removal from plants and the set of readings from each plot was completed in < 4 minutes. Three or four sets of readings were taken each day every c. 2.5 hours from c. 09:00 h to 16:00 h.

All plots were mechanically flailed on 14 September. A final harvest of 36 plants was taken on 6 October. The tubers were graded, counted and weighed in 4 oz increments and a measurement of specific gravity taken from a representative sample of tubers using a Zeal hydrometer. The specific gravity was converted to dry matter concentration using the calibration developed for the hydrometer.

3.8. Commercial fields 2009 and 2010

A number of fields managed by Cambridge University Potato Growers Research Association (CUPGRA) growers and Frontier Agriculture staff were identified in East Anglia prior to planting with soil types ranging from loamy sand to clay where cultivation at planting could lead to soil compaction. Twelve sample areas were identified in each of the 21 (2009) or 26 (2010) selected fields. Three "Locations" were spaced 50 m apart along one edge of the field and identified by using marker stakes and labels along the field boundary. Four "Replicates" were marked at each Location at 50 m intervals along the direction of planting with the first Replicate 50 m from the edge of the field. These areas were accurately mapped so they could be returned to later in the season. Just prior to the primary cultivations at planting, soil water content was measured at 25 cm depth using a Delta-T Devices Theta Probe ML2 and HH2 Moisture Meter by digging a pit 30 cm deep and inserting the Theta Probe horizontally into the face of the pit at 25 cm depth. Four replicate readings were taken at the same depth by moving the Theta Probe across the face of the pit. A soil sample of c. 300 g was taken from each pit at 30 cm depth for three-phase textural classification and determination of organic matter percentage (Walkley Black titration method) at a commercial laboratory (NRM Ltd, Bracknell).

Soil resistance was measured as soon after planting as possible using an Eijkelkamp Penetrograph penetrometer (1 cm2 60° cone tip) at each location. The penetrometer was pushed into the soil mid-way between two plants in the centre of each row. Four readings were taken in each area and averaged. At the same time as soil resistance measurements, a large bulk density core was taken from the centre of the ridge to a depth of 10 cm in the first location. The coring device was either a round aluminium ring of 3.3 l or a steel rectangular box of 2.0 l.

Soil bulk density at 25-30 and 30-35 cm depth below the top of the ridge or bed was measured at each sample area in each field over the period July-September. The depths were measured from the top of the ridge and equate to real depths c. 6-8 cm shallower relative to a flat soil surface. Soil in one row of the bed was excavated to a depth of 25 cm and two replicate cores taken as detailed in Expt 2008. The soil pit was then deepened to 30 cm and the process repeated at this depth. A three-phase soil textural classification was performed on a dried composite sample from 25-35 cm depths at each of the 12 locations (Avery & Bascomb, 1974). Determination of organic matter percentage (Walkley Black titration method) was done at a commercial laboratory (NRM Ltd, Bracknell) on composite samples from three locations (2009) or six locations (2010).

3.9. Statistical analysis

Variates were analysed by analysis of variance using the GenStat Release 8 statistical package (Payne et al. 2005). 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 or figures where standard errors (S.E.) are presented.

4. RESULTS

4.1. Experiment 2008

In Project R406, most measurements were confined to the 200 kg N/ha nitrogen treatments and the degrees of freedom given indicate treatments included in each statistical analysis.

4.1.1. Soil properties

4.1.1.1. Textural analysis

The average textural classification was medium sandy loam but the clay content varied along the length of the experiment (Table 10). The average volumetric stone content (>2mm) taken from bulk density sampling was 10.4 ± 1.5 %.

	Sand			Silt	Clay	Textural
	Coarse	Medium	Fine			Classification
Block 1	1	50	10	23	16	Medium sandy loam
Block 2	2	44	12	24	18	Medium sandy clay loam
Block 3	1	51	13	22	13	Medium sandy loam
Block 4	2	57	11	19	11	Medium sandy loam
Mean	2	51	12	22	14	Medium sandy loam
S.E. (3 D.F.)	0.5	4.3	1.1	1.9	2.4	

TABLE 10. PROPORTIONS OF SAND, SILT AND CLAY (% GRAVIMETRIC) WITHIN THE EXPERIMENTAL AREA IN EXPT 2008

4.1.1.2. Bulk density and porosity

Soil bulk density was measured on four occasions throughout the season. Despite pre-cultivation at a shallow depth in an attempt to reduce the clod size in the final ridge, the Fine cloddiness treatments had similar bulk densities throughout the ridge to Cloddy treatments and therefore only the main effects of cultivation regime are reported.

Bulk density increased in the top 10 cm of soil as the season progressed, indicating a breakdown of the ridge structure and slumping owing to natural weathering and irrigation application (Figure 1). Total pore space in the upper ridge decreased over the same time interval as a consequence of the change in soil structure (Figure 2). In Unsmeared treatments, bulk density in the deepest horizons measured (25-30 and 30-35 cm) tended to decrease (and porosity increase) from June to September, most probably as a consequence of root activity and natural cracking from wetting and drying (Figure 3). In contrast, the bulk density (and porosity) in Smeared soil at these depths remained constant over the same period, probably because of the lower rooting activity (Figure 3). The increase in bulk density at 25-35 cm created by cultivating soil whilst wet rather than dry was c. 0.11 g/cm3, very similar to a comparable experiment in 2007. Porosity is a measure of the soil's capacity to store air and water and generally low porosity can make water less available to plant roots and inhibit root function through anaerobiosis when soils become saturated with water. Cultivating the soil whilst wet had a significant effect on increasing the bulk density and decreasing porosity over the depths where the main cultivation took place (25-35 cm below the top of the ridge; Figure 1 and Figure 2) and the relative differences between the cultivation regimes in these two variables tended to increase as sampling progressed (Figure 1 and Figure 3).

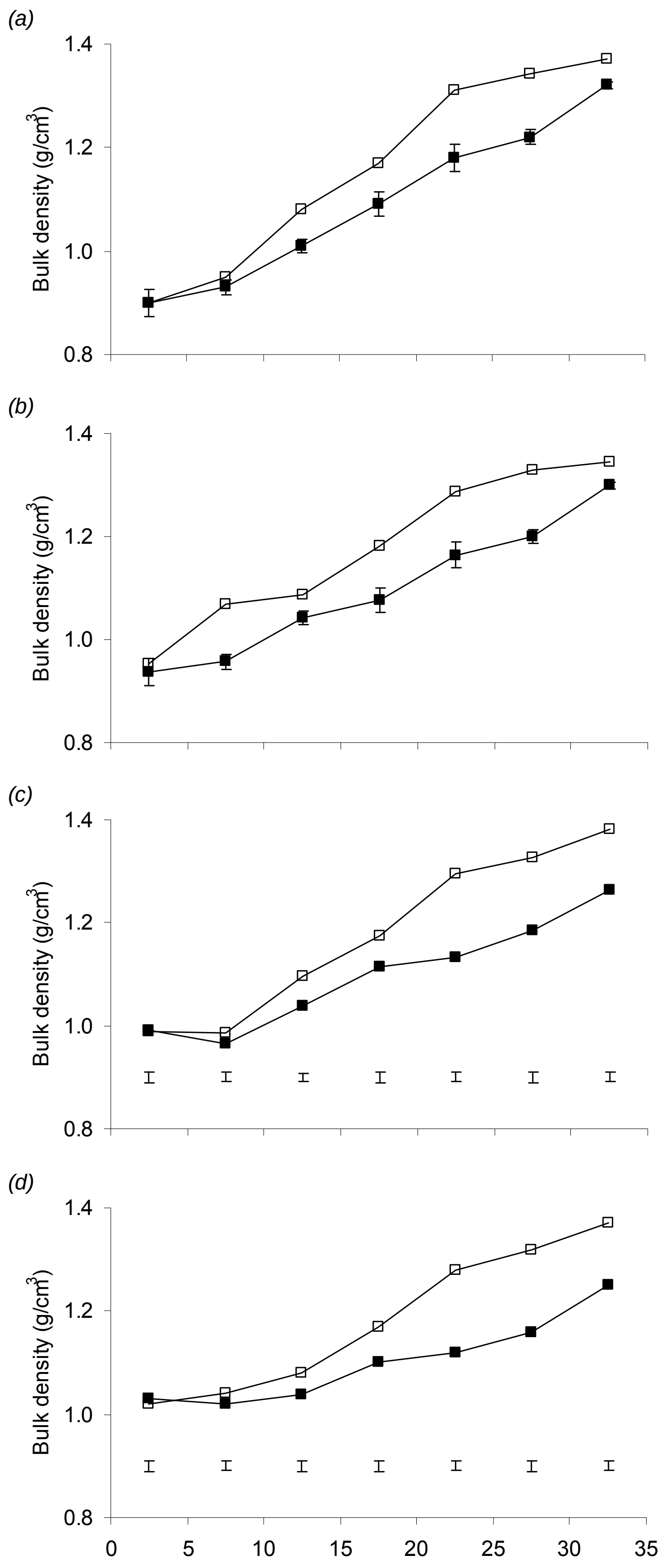

FIGURE 1. SOIL BULK DENSITY ON *(A)* 30 APRIL, *(B)* 5 JUNE, *(C)* 21 AUGUST AND *(D)* 29 SEPTEMBER IN EXPT 2008. UNSMEARED, ■; SMEARED, □. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. S.E. BASED ON 9 D.F.

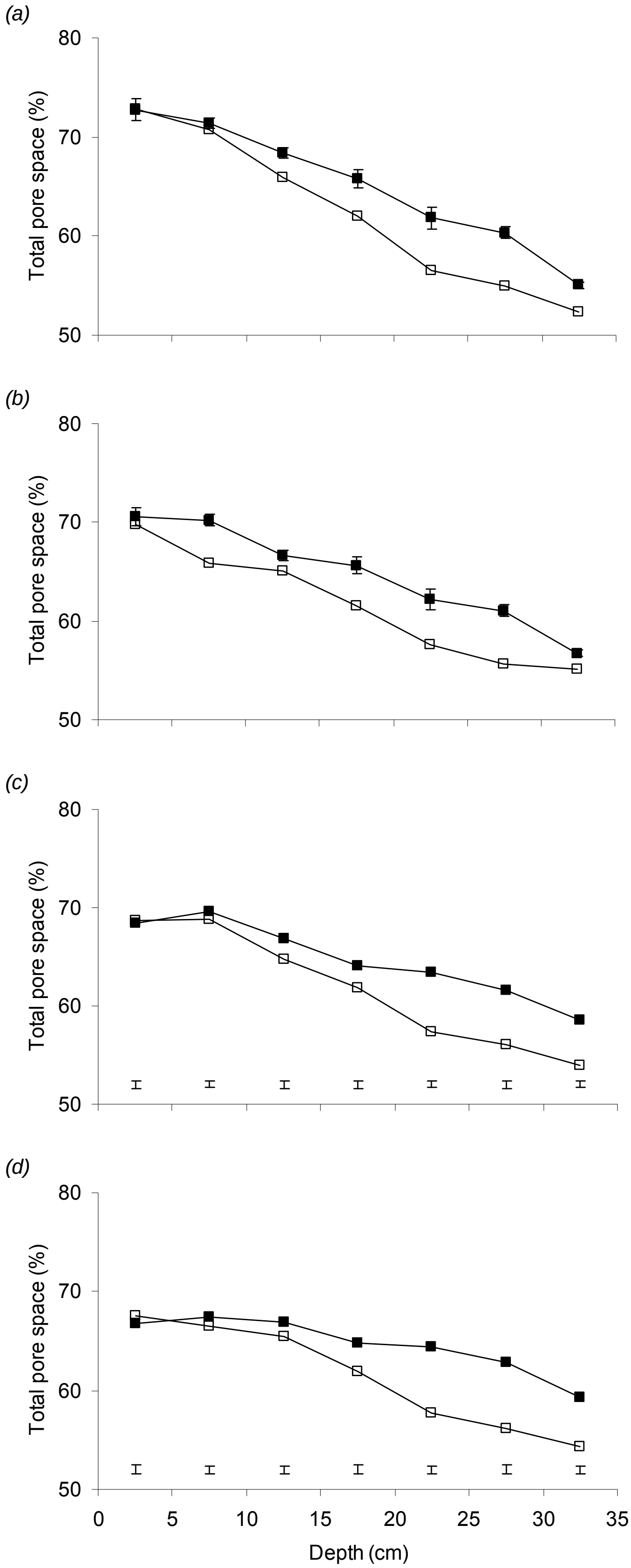

FIGURE 2. TOTAL PORE SPACE ON *(A)* 30 APRIL, *(B)* 5 JUNE, *(C)* 21 AUGUST AND *(D)* 29 SEPTEMBER IN EXPT 2008. UNSMEARED, ■; SMEARED, □. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. S.E. BASED ON 9 D.F.

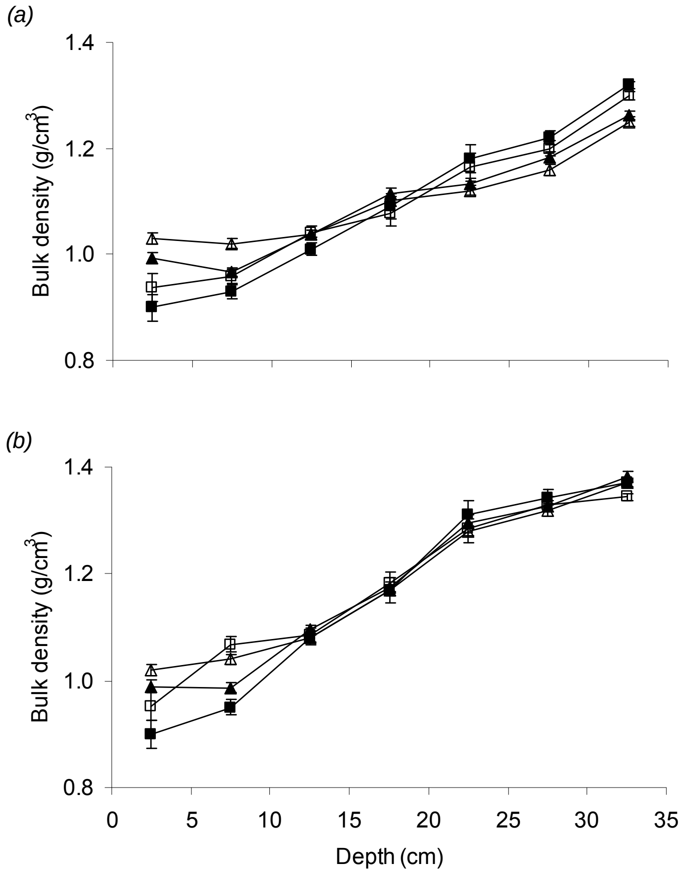

FIGURE 3. TIMECOURSE OF BULK DENSITY IN *(A)* UNSMEARED AND *(B)* SMEARED SOILS IN EXPT 2008. 30 APRIL, ■; 5 JUNE, □; 21 AUGUST, ▲; 29 SEPTEMBER, △. S.E. BASED ON 9 D.F.

Dry bulk density of the ridges to a depth of 20 cm was estimated from the medium-volume soil cores taken for soil grading on 29 April. The amalgamated bulk density estimated from small-volume cores at 0-5, 5-10, 10-15 and 15-20 cm was slightly lower than the medium-volume cores but with neither method was there a significant effect of cultivation treatment (including Cloddy vs Fine) on bulk density in the upper 20 cm of ridge (Table 11).

		Cultivation treatment				
		Unsmeared		**Smeared**		
Method	**Date**	**Cloddy**	**Fine**	**Cloddy**	**Fine**	**S.E.†**
Small-volume	30 April	1.02	0.94	1.04	1.01	0.033
	29 September	1.05	1.04	1.09	1.07	0.017
Medium-volume	29 April	1.07	1.03	1.09	1.07	0.065
	29 September	1.11	1.07	1.14	1.11	0.064

†9 D.F. for S.E. on 29/30 April; 33 D.F. for S.E. on 29 September

TABLE 11. EFFECT OF SOIL CORE VOLUME ON BULK DENSITY (0-20 CM DEPTH) ON TWO SAMPLE DATES IN EXPT 2008

4.1.1.3. Resistance

Four sets of vertical measurements of soil resistance were taken during the season. Resistance on 29 April after the main cultivation and planting showed that Smeared soil was stronger between 25 and 30 cm than soil Unsmeared (Figure 4a) even though the soil water content was similar for both cultivation treatments (8 mm SMD). There was no effect of cloddiness treatments on vertical soil resistance. The resistance increased in the cultivation zone from c. 0.2 MPa to 1.6-1.8 MPa over a depth of 10 cm with the maximum resistance (2.2 MPa) recorded in the subsoil at 50 cm. Root growth rates are generally around one quarter of their maximal rates at resistances of c. 2 MPa, with the ultimate limit for penetration being c. 3 MPa (Stalham et al. 2007). Soil resistance in the upper 35 cm increased slightly between 29 April and 5 June but the same differences between Smeared and Unsmeared soil were apparent (Figure 4b). Additional measurements later in the season were taken from two contrasting irrigation treatments since it has been established that as soils dry, their strength increases and differences in strength between compacted and uncompacted soils can increase. On 4 July, the only significant differences between treatments were between 25 and 30 cm depth. Smeared soil had significantly greater resistance at these depths than Unsmeared and Unirrigated soils were more resistant than Irrigated (Figure 5a). The Unirrigated soils were dry at this stage (50 mm SMD) whereas the Irrigated were quite moist (9 mm SMD) and the resistance exceeded 3 MPa in Unirrigated crops, irrespective of cultivation regime, albeit for a limited depth in the soil. There was a slightly, but significantly, bigger difference in resistance between Smeared and Unsmeared soils where the soils were dry than where they were moist. By 24 July, even though the SMD (53 mm) was similar in rainfed plots to 4 July, soils in Unirrigated crops had dried to considerable depth and the soil was significantly harder at all depths below 25 cm than Irrigated but the difference between irrigation regimes at 25 and 30 cm was smaller on 24 July than on 4 July (Figure 5b). The SMD was 36 mm in the Irrigated plots at this stage. Smeared soil still had a significantly greater resistance than Unsmeared at the cultivation depth (25-30 cm) and, unlike 4 July, there was no effect of irrigation regime on this difference on 24 July.

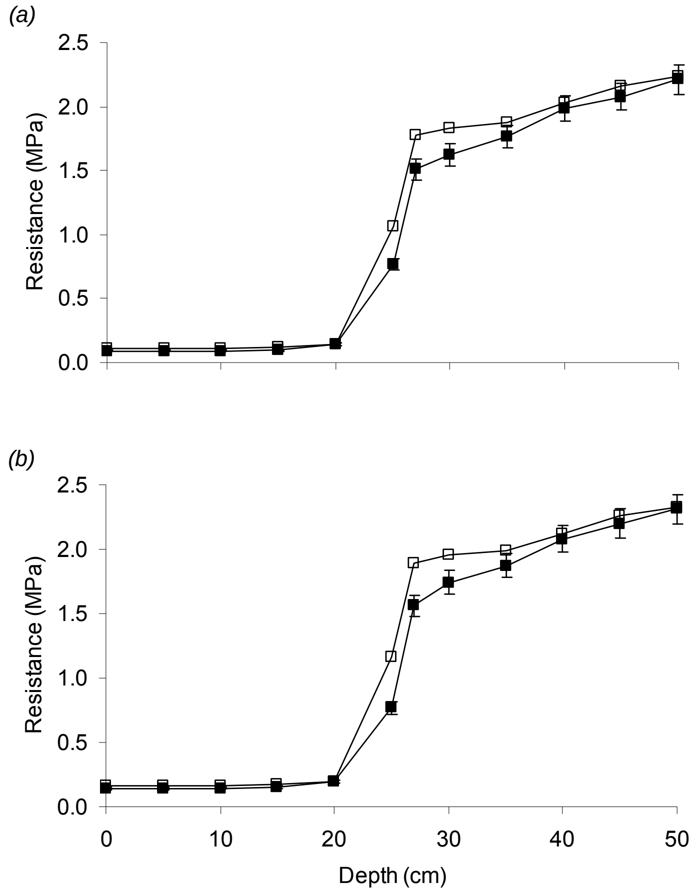

FIGURE 4. VERTICAL SOIL RESISTANCE ON (A) 29 APRIL AND (B) 5 JUNE IN EXPT 2008. UNSMEARED, ■; SMEARED, □. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. SOIL MOISTURE DEFICITS: (A) 8 MM; (B) 0 MM. S.E.S BASED ON 9 D.F.

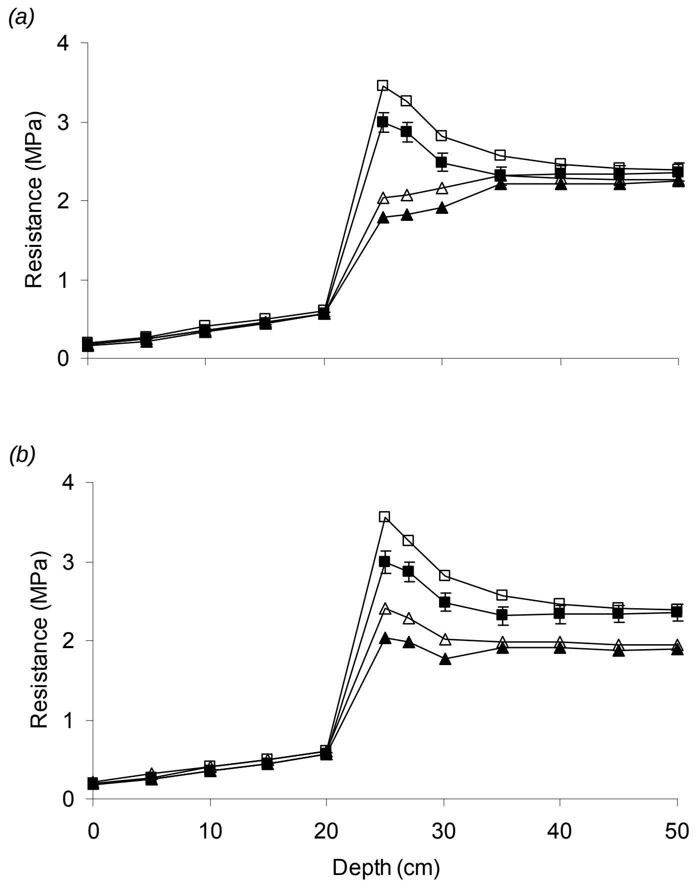

FIGURE 5. VERTICAL SOIL RESISTANCE ON (A) 4 JULY AND (B) 24 JULY IN EXPT 2008. UNSMEARED UNIRRIGATED, ■; SMEARED UNIRRIGATED □; UNSMEARED IRRIGATED, ▲; UNSMEARED IRRIGATED, △. DATA ARE MEAN OF BOTH CLODDINESS TREATMENTS. SOIL MOISTURE DEFICITS: (A) UNIRRIGATED 50 MM; IRRIGATED 9 MM; (B) UNIRRIGATED 51 MM; IRRIGATED 33 MM. S.E.S BASED ON 21 D.F.

Horizontal measurements of soil resistance with a Pesola penetrometer on two occasions showed that Smeared soil was stronger at the base of the ridge than Unsmeared soil. As the soil dried between the 5 June and 4 July, the soil strength increased but the differences between Unsmeared and Smeared soil remained (Table12). Pre-cultivation with a rotavator did not change the soil resistance in the ridge so that this was similar for Fine and Cloddy treatments.

		Soil treatment				
Date		**Unsmeared Cloddy**	**Unsmeared Fine**	**Smeared Cloddy**	**Smeared Fine**	**S.E. (9 D.F.)**
5 June	Resistance	0.41	0.42	0.66	0.62	0.051
	Water content	25.7	25.1	24.8	25.1	1.14
4 July	Resistance	0.49	0.49	0.74	0.69	0.052
	Water content	22.5	22.0	21.7	21.9	1.00

TABLE 12. SOIL RESISTANCE (MPA) AND WATER CONTENT (% VOLUMETRIC) AT THE BASE OF THE RIDGE ON 5 JUNE AND 4 JULY IN EXPT 2008

4.1.1.4. Water holding capacity

When comparing water holding capacity on a gravimetric basis (i.e. g water/g soil), the quantities of both very easily available (< 60 kPa potential) and easily available (200 kPa) water were decreased by cultivating the soil whilst wet compared with dry cultivation (Table 13a). However, owing to the significant increase in bulk density caused by soil compaction, Smeared treatments had higher volumetric available water holding capacities at both very easily and easily available tensions than Unsmeared (Table 13b). Usually, compaction increases the absolute water holding capacity of most soils by increasing the proportion of fine pores spaces and reducing the number of large pores space where water is held more freely. Generally, as long as the water is held at tensions < 1500 kPa, it is available to the roots of most crops. However, potato roots have a much lower ability to create suction than cereals, with their limit being typically 400-700 kPa (Campbell 1972), therefore they cannot extract water from very fine pores. Correspondingly, the loss of large pore spaces with compaction in most soils other than sands can decrease the amount of water available to potatoes. In contrast to the directional changes in water holding capacity with compaction, root penetration is significantly decreased by compaction (Stalham et al. 2007) and the consequent lower RLD decreases the capacity to take up water irrespective of the tensions with which water is held between peds. The effect of soil cultivation on rooting is covered later in this report (p. 38).

	Depth (cm)			
	15-20 cm		**25-30 cm**	
Water potential (bar)	**0.6**	**2.0**	**0.6**	**2.0**
(a) % gravimetric				
Unsmeared	17.8	15.6	18.9	16.2
Smeared	17.0	14.9	17.8	15.7
S.E. (9 D.F.)	0.24	0.22	0.32	0.37
(b) % volumetric				
Unsmeared	19.1	16.7	22.6	19.4
Smeared	20.0	17.5	23.6	20.9
S.E. (9 D.F.)	0.37	0.27	0.36	0.45

TABLE 13. AVAILABLE WATER HOLDING CAPACITY ON *(A)* GRAVIMETRIC AND *(B)* VOLUMETRIC BASIS IN EXPT 2008. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. OVER-IRRIGATED TREATMENTS ONLY

4.1.1.5. Ped size distribution

There are two main ways of examining ped size distribution: (a) the proportion of soil in each ped size grade and (b) the mean ped size. For the purposes of analysis, the ped size classes were amalgamated into pairs at the larger grades (6-15, 15-25, 25-35 and 35-45 mm). Wet sieving of large-volume samples taken pre-planting, post-main cultivation and 8 and 22 weeks later showed that mean ped size decreased over time and the proportion of ped in the larger sizes was reduced. Mean ped size was significantly greater in Cloddy plots (13.1 ± 0.75 mm) than Fine (10.9 mm) on 25 April (pre-main cultivation but post-rotavation), mainly as a consequence of a much greater proportion of 35-45 mm peds in Cloddy treatments (Figure 6). There were no significant differences in any other ped size class. Averaged over both cloddiness treatments, there was 17.1 ± 0.89 % of the soil in the fraction that would be classified as a soil textural unit, i.e. < 2 mm.

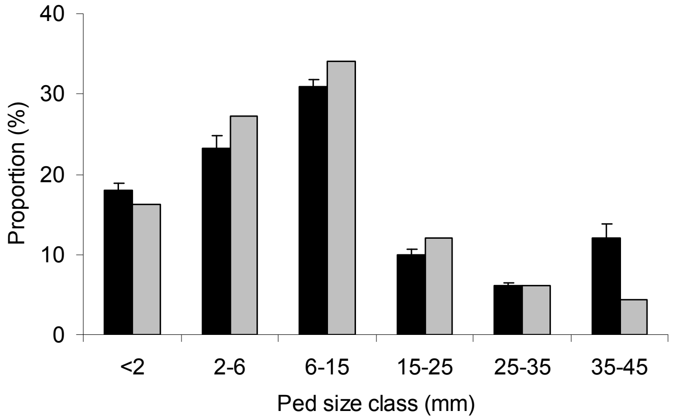

FIGURE 6. PED SIZE DISTRIBUTION ON 25 APRIL IN EXPT 2008. CLODDY, ■; FINE, ■. DATA TAKEN PRIOR TO MAIN CULTIVATION. S.E.S BASED ON 3 D.F.

Following the main Rototiller cultivation and planting on 28-29 April, mean ped size had decreased to 8.5 ± 0.35 mm and the fraction of soil < 2 mm had increased to 32.6 ± 1.46 % and neither variable was affected by cultivation or cloddiness regimes (Figure 7a). By 19 June, mean ped size had not changed (8.4 ± 0.47 mm) but the fraction of soil < 2 mm had increased to 35.5 ± 2.11 % (Figure 7b). The final sampling on 29 September showed that mean ped size had decreased further (6.8 ± 0.40 mm) and the fraction of soil < 2 mm had increased to 39.3 ± 2.33 % (Figure 7c). Following planting, there were no significant differences between cultivation or cloddiness regimes in the fraction of peds in any size class, with the major reduction in ped size occurring during cultivation at planting. However, there was still some destructuring of the ridge profile during the rest of the season as the soil weathered.

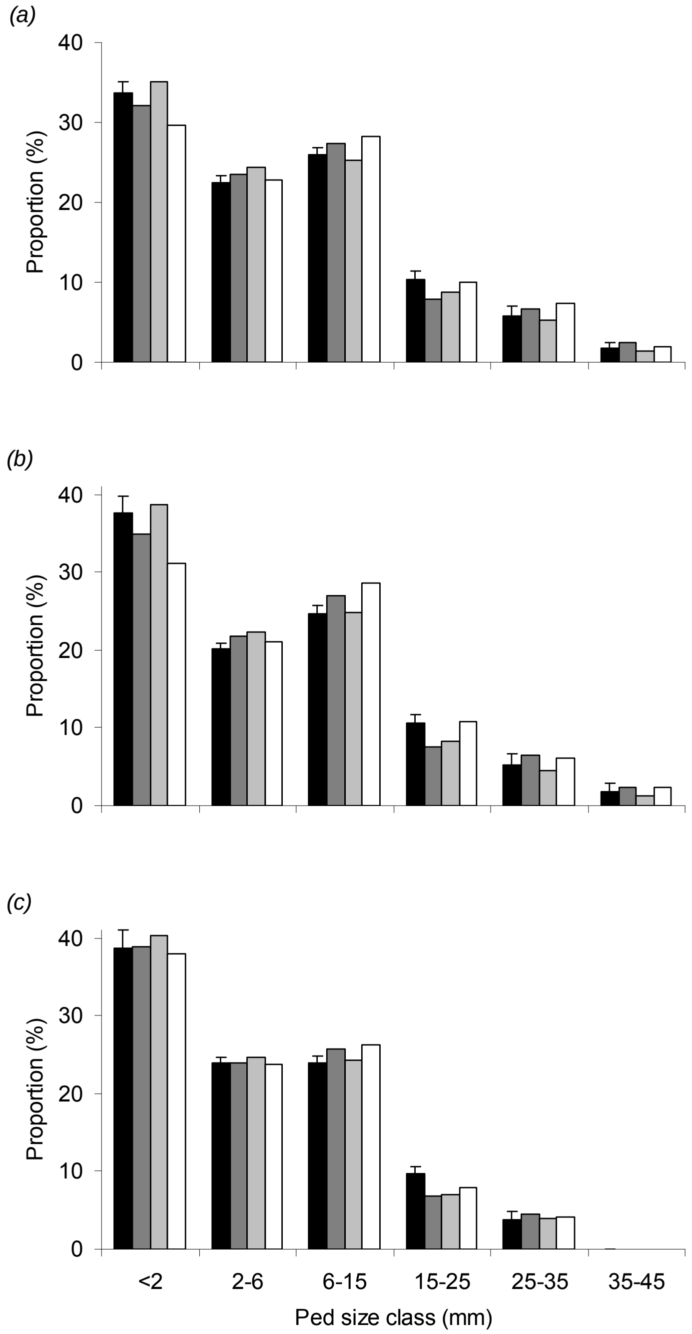

FIGURE 7. PED SIZE DISTRIBUTION ON *(A)* 29 APRIL, *(B)* 19 JUNE AND *(C)* 29 SEPTEMBER IN EXPT 2008. UNSMEARED CLODDY, ■; UNSMEARED FINE, ■; SMEARED CLODDY, ■; SMEARED FINE, □. S.E.S BASED ON 9 D.F.

Soil grading carried out on 29 April and 29 September using a medium-volume (0.91 l) sample dried before sieving produced similar results to grading large-volume fresh samples and showed no significant differences in soil grading as a result of contrasting cultivation regimes (data not shown). The drying stabilized the peds pre-sieving, so it would be a better technique where soils are sampled wet and there is a risk of (a) compressing soil into artificial peds and (b) having to use over-aggressive sieving to separate different ped sizes.

4.1.1.6. Soil moisture deficits and soil water content

The season was characterised by a consistently moderate evapotranspiration (ET) demand during June and July, a higher than average demand in May and a substantially lower than average demand during August and September. There were no sustained hot periods but there were periods when there was no significant rainfall (first half of June and the second half of July). Soil moisture deficits calculated by the CUF Irrigation Scheduling Model increased above the SMD which limits growth (Limiting SMD) in Unirrigated plots during dry spells in early July and from late July to early August but the Irrigated plots were maintained below the Limiting SMD for almost the entire season (Figure 8). Over-irrigated treatments were maintained at < 25 mm SMD throughout, with five significant drainage events (mean 20.2 mm) between 3 July and 14 August following frequent irrigation. The overall drainage from emergence to final harvest was: Unirrigated 40 mm, Irrigated 89 mm and Over-irrigated 229 mm.

The measurements of soil water content taken using the Theta probes were converted into SMDs based on the values for Field Capacity on 31 May, two days after 41 mm of rainfall. A model was used to convert the readings at 25 and 50 cm depths into an overall SMD but there is some weakness in this approach in that the SMD in the upper ridge profile is poorly estimated by this technique. Estimates of water use calculated by the CUF Irrigation Scheduling Model and changes in the SMD measured by Theta Probe appeared to be close in Unirrigated treatments but modelled SMDs were greater than measured in the both irrigated treatments, particularly during August and September (Figure 8). Measured SMDs in Smeared soil were greater than in Unsmeared, mostly as a consequence of differences in SMD at the 25 cm depth, indicating a shallower zone of water uptake by crops grown in compacted soil.

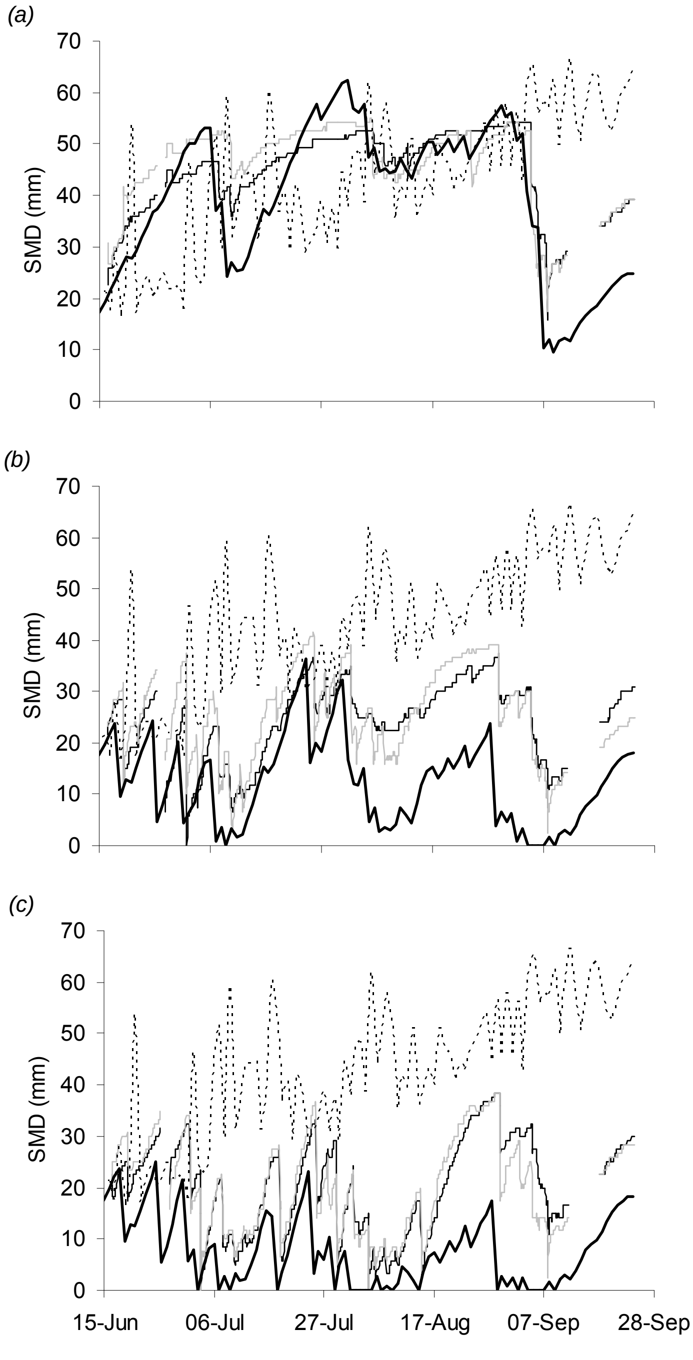

FIGURE 8. MEASURED (BASED ON THETA PROBE MEASUREMENTS AT TWO DEPTHS ONLY, 25 AND 50 CM) AND MODELLED SOIL MOISTURE DEFICITS (SMD) IN EXPT 2008. (A) UNIRRIGATED, (B) IRRIGATED AND (C) OVER-IRRIGATED. UNSMEARED MEASURED, —; SMEARED MEASURED, —; MODELLED, ▬; LIMITING SMD, ---. DATA FOR MODELLED ARE MEAN OF UNSMEARED AND SMEARED TREATMENTS.

4.1.2. Plant measurements

4.1.2.1. Emergence, ground covers and radiation absorption

The mean date for 50 % plant emergence was 26 May (28 days after planting) and soil conditions (smearing or cloddiness) had no significant effect on plant emergence, however, increasing the N application rate from 0 to 200 kg N/ha delayed 50 % emergence by c. 1 day. Complete emergence was achieved in most plots. The effects of irrigation regime, soil condition (Smeared and Unsmeared) and N application rate on ground cover are shown in Figure 9 and key ground cover data and radiation absorption data are shown in Table 14. Maximum ground cover was significantly increased by applying irrigation, growing the crop in Unsmeared soil and applying 200 kg N/ha. Applying 200 kg N/ha resulted in complete ground cover irrespective of soil conditions or the amount of irrigation applied. The rate of increase of ground cover was estimated from the parameters of a logistic (growth) curve fitted to pre-senescence ground cover data. The rate of increase of ground cover was increased by applying irrigation and N and when the crop was grown in Unsmeared soils compared with Smeared. The average canopy persistence was 8927 % days and, when averaged over other factors, was increased by c. 800 % days when irrigation was applied and by c. 1400 % days when the N application rate was increased from 0 to 200 kg N/ha. Growing the crop in Smeared soil reduced canopy persistence by a smaller amount (c. 500 % days) than irrigation or N. The fineness of soil in the ridge had no significant effect on the maximum ground cover attained, the rate of ground cover expansion or integrated ground cover. Radiation absorption was increased by N and water but was decreased when the crops was grown in Smeared soil (Table 14 Table 14). Soil cloddiness had no statistically significant effect on radiation absorption by the crop.

	Maximum ground cover (%)	**Maximum ground cover (angularly transformed)**	**Rate of ground cover increase, (%/day)**	**Integrated ground cover (% days)**	**Radiation absorption (TJ/ha)**
Unirrigated	93.7	81.2	3.10	8324	12.4
Irrigated	97.5	85.4	3.54	9180	13.5
Over-irrigated	98.4	87.3	3.56	9277	13.6
S.E. (33 D.F.)	-	1.30	0.102	127.8	0.18
Unsmeared	97.7	86.4	3.66	9197	13.6
Smeared	95.4	82.8	3.14	8657	12.8
S.E. (33 D.F.)	-	1.06	0.083	104.3	0.15
Cloddy tilth	96.6	84.7	3.47	9049	13.3
Fine tilth	96.5	84.5	3.32	8805	13.0
S.E. (33 D.F.)	-	1.06	0.083	104.3	0.15
0 kg N/ha	93.1	79.2	2.71	8210	12.2
200 kg N/ha	100.0	90.0	4.09	9643	14.2
S.E. (36 D.F.)	-	1.07	0.064	104.2	0.14

TABLE 14. MAIN EFFECTS OF IRRIGATION, CULTIVATION AND N APPLICATION RATE ON MAXIMUM GROUND COVER, THE RATE OF GROUND COVER EXPANSION FROM 40 TO 60 % GROUND COVER, SEASON-LONG INTEGRATED GROUND COVER AND RADIATION ABSORPTION IN EXPT 2008

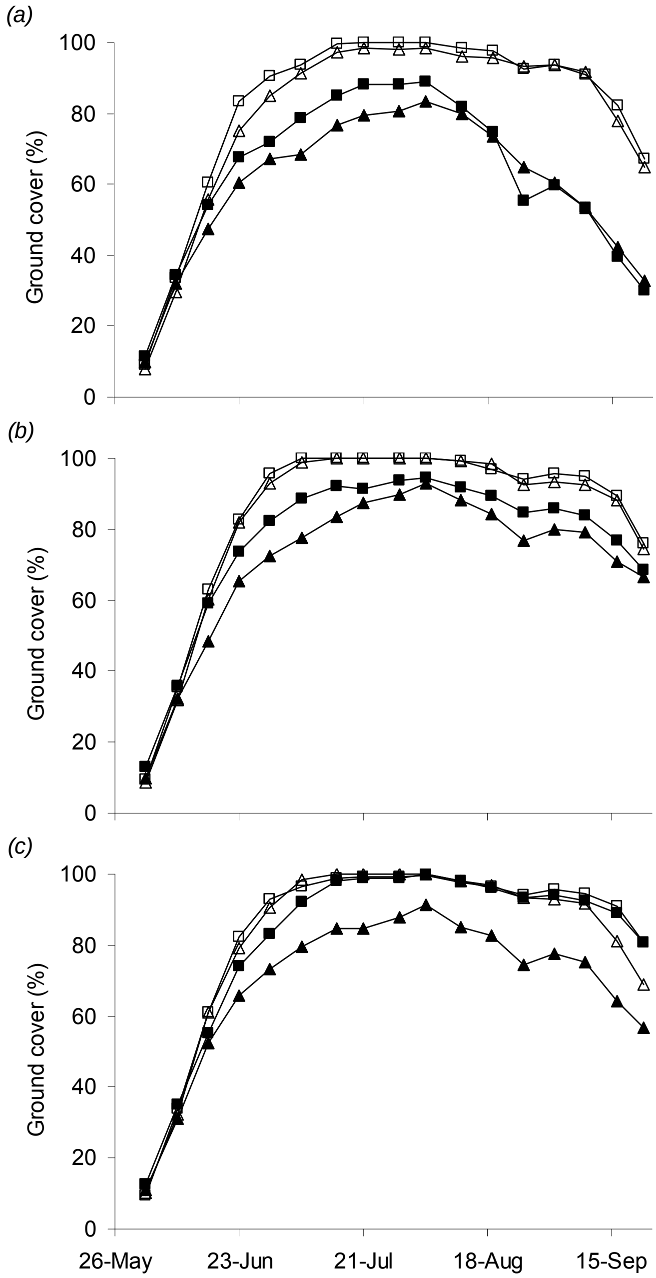

FIGURE 9. EFFECT OF SOIL CULTIVATIONS, IRRIGATION AND N APPLICATION RATE ON DEVELOPMENT OF GROUND COVER IN EXPT 2008. (A) UNIRRIGATED, (B) IRRIGATED AND (C) OVER-IRRIGATED. UNSMEARED N0, ■; UNSMEARED N200, □; SMEARED N0, ▲; SMEARED N200, △. DATA ARE MEAN OF BOTH CLODDINESS TREATMENTS.

4.1.2.2. Rooting density

Root length density was only examined in the soil horizons where there were significant differences measured in soil bulk density (20-25, 25-30 and 30-35 cm depth) and in Cloddy treatments only as there were no differences in soil bulk density between cloddiness treatments at these depths. In general, RLD was slightly lower than previous RLDs found at CUF over the period 1988-1993. On 8 July, Smeared soil had lower RLD than Unsmeared in the horizons where the curved tips of rotavator tines were working (25-30 and 30-35 cm; Figure 10a). The reduction in RLD of c. 14 % (25-30 cm) and 16 % (30-35 cm) between Smeared and Unsmeared was greater than the proportional increase in soil bulk density at these depths (c. 10 %). There was a significant increase in RLD in Smeared treatments compared with Unsmeared at 20-25 cm, the soil horizon above where cultivation took place, suggesting that root proliferation increased as a consequence of being unable to penetrate the stronger soil in the cultivation zone when soils were wet at the main cultivation. This was despite the soil bulk density being 1.30 g/cm3 in Smeared soil and 1.17 g/cm3 in Unsmeared soil. As found previously (Stalham & Allen 2001), keeping soils wet through irrigation during early season increased RLD in the 20-35 cm horizon compared with Unirrigated soils.

By 21 August, RLD had decreased by c. 16-20 % in all measured horizons compared with 8 July but irrigated crops still had greater RLD than Unirrigated. There was no significant difference in RLD between cultivation regimes in the shallowest horizon measured but Smeared soil still had lower RLD than Unsmeared in the two deeper horizons (Figure 10b).

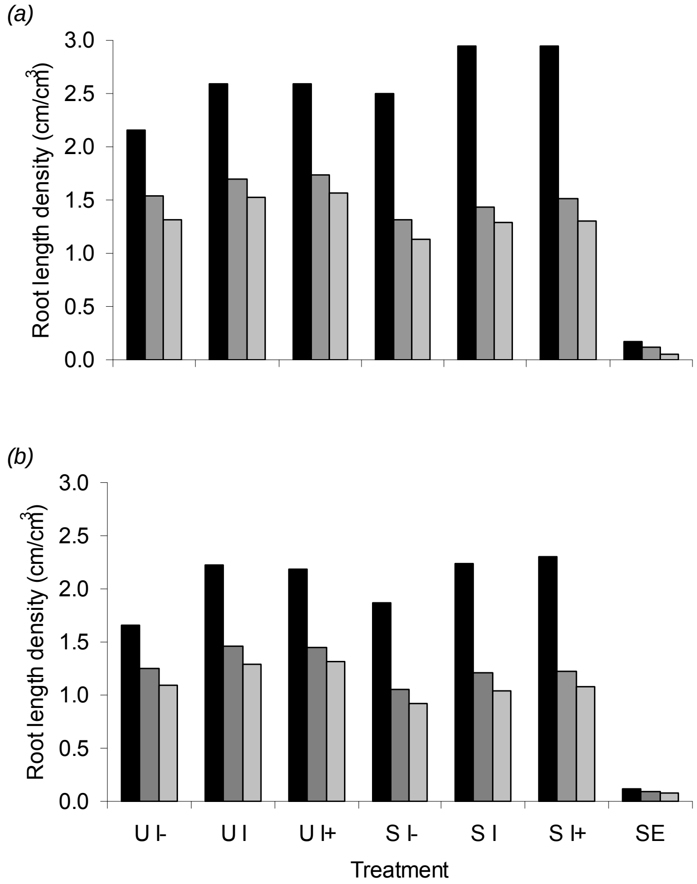

FIGURE 10. ROOT LENGTH DENSITY ON (A) 8 JULY AND (B) 21 AUGUST IN EXPT 2008. UNSMEARED, U; SMEARED, S; UNIRRIGATED, I-; IRRIGATED, I; OVER-IRRIGATED, I+. DEPTHS: 20-25 CM, ■; 25-30 CM, ■; 30-35 CM, ■. CLODDY TREATMENTS ONLY. S.E. BASED ON 15 D.F.

4.1.2.3. Leaf and tuber water potential

Leaf WP was generally low throughout the season even in Unirrigated plots with the exception of a period in early July when WPs of > 10 bar were observed. Smeared soil increased leaf WP significantly compared with Unsmeared soil at virtually every date of sampling, albeit the differences were small compared with differences recorded between irrigation treatments (Figure 11a). For most of late July and early August, Unirrigated crops had higher leaf WP than irrigated (Figure 11b) but the differences were small compared with previous findings.

Tuber WPs were roughly half the values of leaf WP, even when leaf WPs were > 10 bars. Similar to leaf WP, crops grown in Smeared soil had slightly, but significantly, greater tuber WP than those in Unsmeared soil on most days (Figure 12a). For most of late July and early August, Unirrigated crops had higher tuber WP than irrigated (Figure 12b) but the differences were small compared with previous work on other varieties (e.g. Lady Rosetta) at CUF.

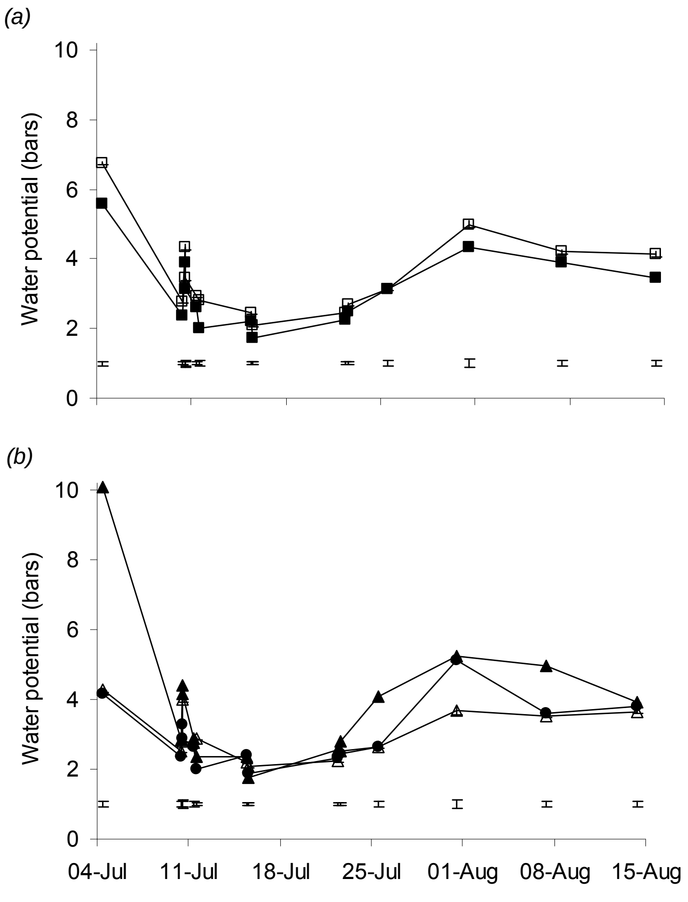

FIGURE 11. LEAF WATER POTENTIAL IN EXPT 2008. MAIN EFFECT OF (A) CULTIVATION AND (B) IRRIGATION TREATMENTS. UNSMEARED, ■; SMEARED □; UNIRRIGATED, ▲; IRRIGATED, △; OVER-IRRIGATED, ●. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. S.E. BASED ON 33 D.F.

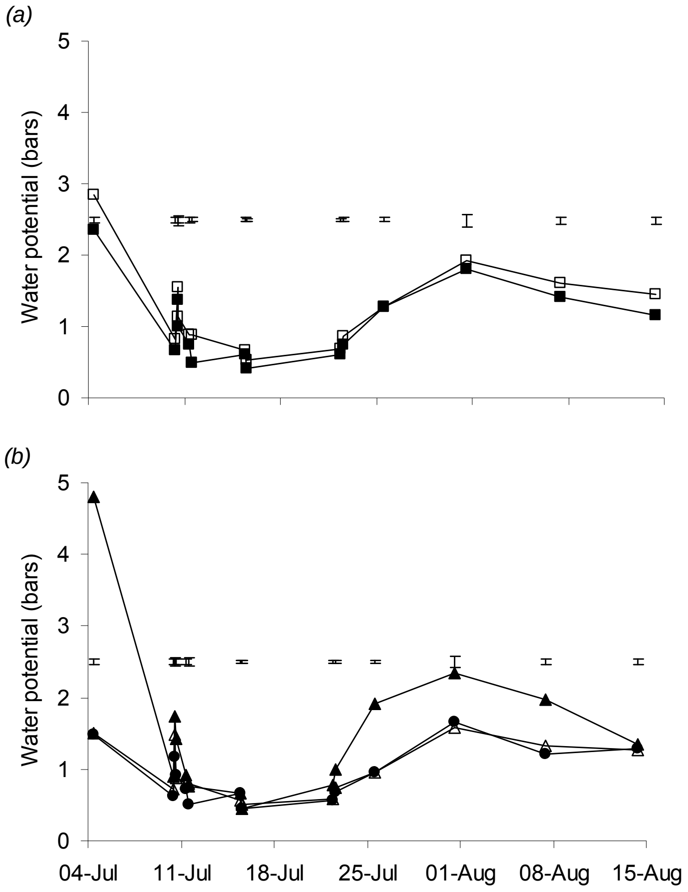

FIGURE 12. TUBER WATER POTENTIAL IN EXPT 2008. MAIN EFFECT OF *(A)* CULTIVATION AND *(B)* IRRIGATION TREATMENTS. UNSMEARED, ■; SMEARED □; UNIRRIGATED, ▲; IRRIGATED, △; OVER-IRRIGATED, ●. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. S.E. BASED ON 33 D.F.

Previous experiments have shown that leaf WP can increase rapidly on hot days, with tuber WP increasing after a lag and at a slower rate. Tubers appear to be used as a source of water to maintain leaf WP and delay the onset of stomatal closure and leaf wilting. The magnitude of the response in leaf and water WP differs depending on whether the soil is dry or wet at the start of the day and the evaporative demand of the atmosphere. On cool days, there was often only a small change in leaf WP and no alteration in tuber WP.

On four days in the experiment in 2008, leaf and tuber WP were taken on two occasions during the day, typically 9:00 and 15:00 h. On 10 and 22 July, there was an increase in WP of both organs between 9:00 and 15:00 h and the increase was greater in Unirrigated than in Irrigated or Over-irrigated and the increases in WP were greater in leaves than in tubers (Table 15). On 10 July, ET0 demand was slightly above average and SMDs in all irrigation treatments were low so the increases in WP during the day were small. On 22 July, SMDs were higher than on other dates but ET0 demand was low and the increase in WP was again small. On 11 and 15 July, leaf and tuber WPs decreased between 9:00 and 15:00 h as, despite there being slightly above-average ET0 during the day, the afternoons were cooler and duller than the morning and plants were able to re-balance their water supply from root uptake, even in Unirrigated crops where the SMD was 31 mm.

Date	ET0 (mm)	Time	Leaf Un-irrigated	Leaf Irrigated	Leaf Over-irrigated	Leaf S.E.	Tuber Un-irrigated	Tuber Irrigated	Tuber Over-irrigated	Tuber S.E.
10 July	3.57	9:00	2.84	2.51	2.36	0.127	0.90	0.72	0.62	0.059
		15:00	4.16	2.81	2.88	0.141	1.42	0.88	0.92	0.065
		Diff.	1.31	0.30	0.52	0.192	0.52	0.16	0.30	0.089
SMD at 9:00 (mm)			24	0	0	1.2				
11 July	3.27	9:00	2.88	2.77	2.66	0.126	0.92	0.80	0.73	0.059
		15:00	2.36	2.89	2.01	0.117	0.76	0.81	0.51	0.110
		Diff.	-0.53	0.12	-0.53	0.154	-0.17	0.01	-0.22	0.075
SMD at 9:00 (mm)			27	3	3	1.6				
15 July	3.85	9:00	2.37	2.20	2.40	0.108	0.67	0.56	0.67	0.050
		15:00	1.74	2.09	1.87	0.100	0.46	0.51	0.45	0.046
		Diff.	-0.63	-0.12	-0.53	0.128	-0.21	-0.05	-0.22	0.059
SMD at 9:00 (mm)			31	8	8	2.3				
22 July	2.87	9:00	2.55	2.22	2.31	0.091	0.78	0.59	0.56	0.038
		15:00	2.80	2.53	2.45	0.111	1.00	0.75	0.68	0.051
		Diff.	0.25	0.31	0.14	0.156	0.22	0.16	0.12	0.073
SMD at 9:00 (mm)			46	27	12	2.6				

TABLE 15. EFFECT OF IRRIGATION REGIME ON DIFFERENCE IN LEAF AND TUBER WATER POTENTIALS (BARS) AT 9:00 AND 15:00 H, ET_0 AND SMD ON FOUR DATES IN EXPT 2008. VALUES ARE MEANS OF BOTH CULTIVATION AND CLODDINESS REGIMES. S.E. BASED ON 33 D.F. EXCEPT ON 15 JULY WHERE 22 D.F. ONLY AS ONLY THREE REPLICATES MEASURED

There was a close correlation between tuber WP and leaf WP for readings taken at the same time of day (9:00 h) and this relationship was unaffected by cultivation or irrigation treatments (Figure 13). If treatments caused an increase in leaf WP, they also resulted in a similar increase in tuber WP. This suggests that the same balance between tuber and leaf WP was maintained even when the plant was under water stress as indicated by SMD and leaf WP.

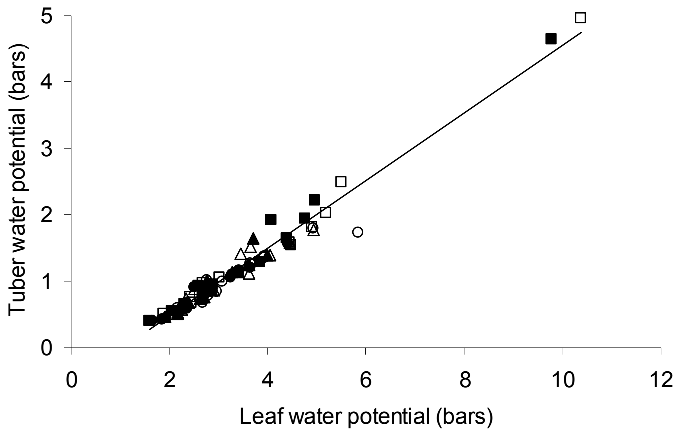

FIGURE 13. RELATIONSHIP BETWEEN TUBER AND LEAF WATER POTENTIAL IN EXPT 2008. UNIRRIGATED, ■; IRRIGATED, ▲; OVER-IRRIGATED, ●. CLOSED SYMBOLS UNSMEARED, OPEN SYMBOLS SMEARED. EQUATION OF LINE, Y = 0.509 ± 0.0450 X - 0.54 ± 0.040, R2=0.96. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS.

4.1.2.4. Stomatal resistance

There were much smaller differences in SR between treatments than expected. There was a dry, hot spell at the beginning of July which resulted in Unirrigated crops having much higher SR than crops receiving irrigation, however for much of the season there were relatively small differences across irrigation treatments as evaporative demand was low even when SMDs were high in Unirrigated plots. Plants grown in Smeared soil had a small and consistently (and in most cases significantly) greater SR than Unsmeared. The mean value for Unsmeared soil (2.63 ± 0.062 s/m) over all sample dates was significantly lower than Smeared (2.82 s/m). This indicates that water stress resulting from soil compaction was apparently causing partial stomatal closure even when soils were kept wet through irrigation (Figure 14).

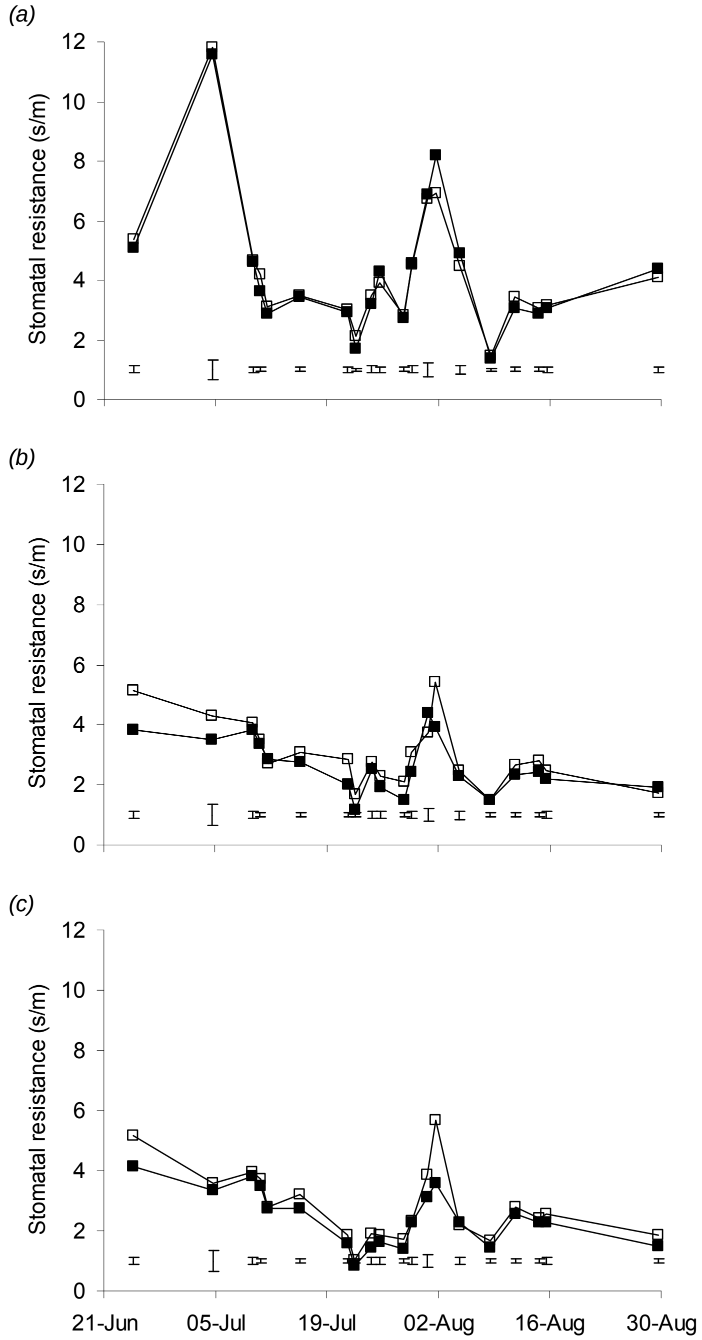

FIGURE 14. STOMATAL RESISTANCE MEASURED AT 15:00 H IN (A) UNIRRIGATED, (B) IRRIGATED AND (C) OVER-IRRIGATED PLOTS IN EXPT 2008. UNSMEARED, ■; SMEARED, □. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. S.E.S BASED ON 33 D.F.

As with WP, on a number of days, SR was measured on two or more occasions, typically the first set beginning at 9:00 h and then repeated mid-afternoon (15:00 h). There were a greater number of occasions when repeated measurements of SR were made than for WP. Where SR increased during the day, there was a larger change in Unirrigated crops than in those receiving irrigation (Figure 15a). There were occasional unexpected differences in the magnitude of the change in SR between Irrigated and Unirrigated treatments. For example, on 25 July and 1 August there was a larger increase in SR during the day in Over-irrigated crops than in Irrigated. On 25 July, Over-irrigated plots started the day with very low SR (0.99 ± 0.192 s/m) compared with Irrigated (2.12 s/m). There was an irrigation event of 24 mm starting at 9:00 h on 25 July immediately after the first readings of SR were taken. This brought the water content of soils in Over-irrigated plots to greater than Field Capacity but left a deficit of 16 mm in Irrigated plots. On 1 August, as well as the readings of SR at 9:00 h, two sets of readings were taken immediately before and after 18 mm of irrigation was applied and the increase in SR pre- and post-irrigation was greater in Over-irrigated (2.66 ± 0.253 to 4.64 ± 0.272 s/m) than in Irrigated (3.85 to 4.68 s/m). On this occasion, the soil was over-filled by c. 10 mm in Over-irrigated plots and the response in SR could be a consequence of water-logging.

There was generally no significant effect of cultivation regime on the magnitude of the change in SR. On average, Smeared crops had greater SR during the season than Unsmeared but increases or decreases during the course of the day were the same for both cultivation regimes. These SR data need to be considered more carefully in relation to ET0 demand and SMD but more data from hot, high ET0 days are required to extend the range.

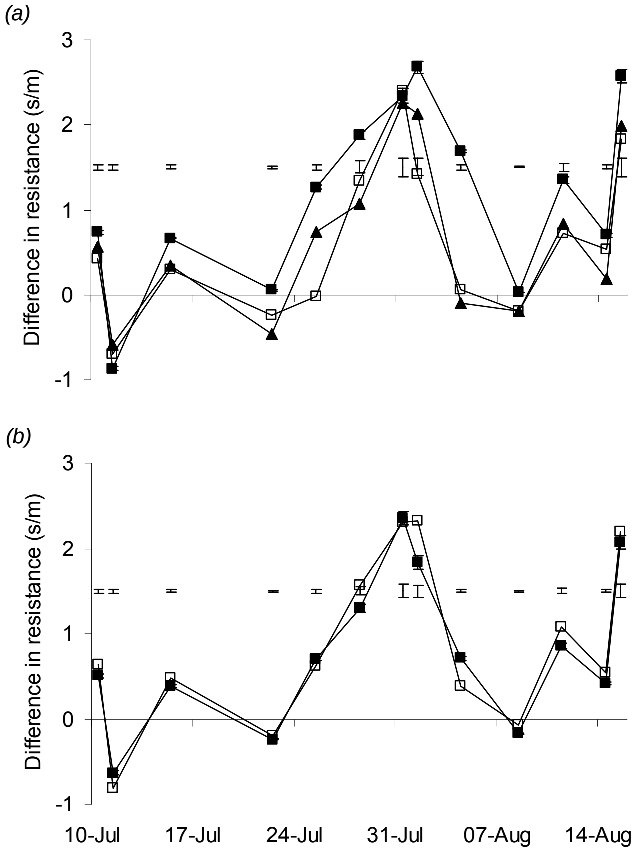

FIGURE 15. DIFFERENCE IN STOMATAL RESISTANCE BETWEEN 9:00 AND 14:00 H DURING JULY AND AUGUST IN EXPT 2008. TREATMENT MEANS FOR (A) IRRIGATION AND (B) CULTIVATION. UNIRRIGATED, ■; IRRIGATED, □; OVER-IRRIGATED, ▲; UNSMEARED, ●; SMEARED, ○. DATA ARE MEANS OF BOTH CLODDINESS TREATMENTS. S.E. BASED ON 33 D.F.

There was no relationship between SR and tuber WP for irrigated treatments for readings taken at the same time of day. There was, however, a significant linear relationship between these two variables in Unirrigated crops although at low WP there was a poor relationship (Figure 16). Cultivation regime (smearing or cloddiness) had no effect on the relationship.

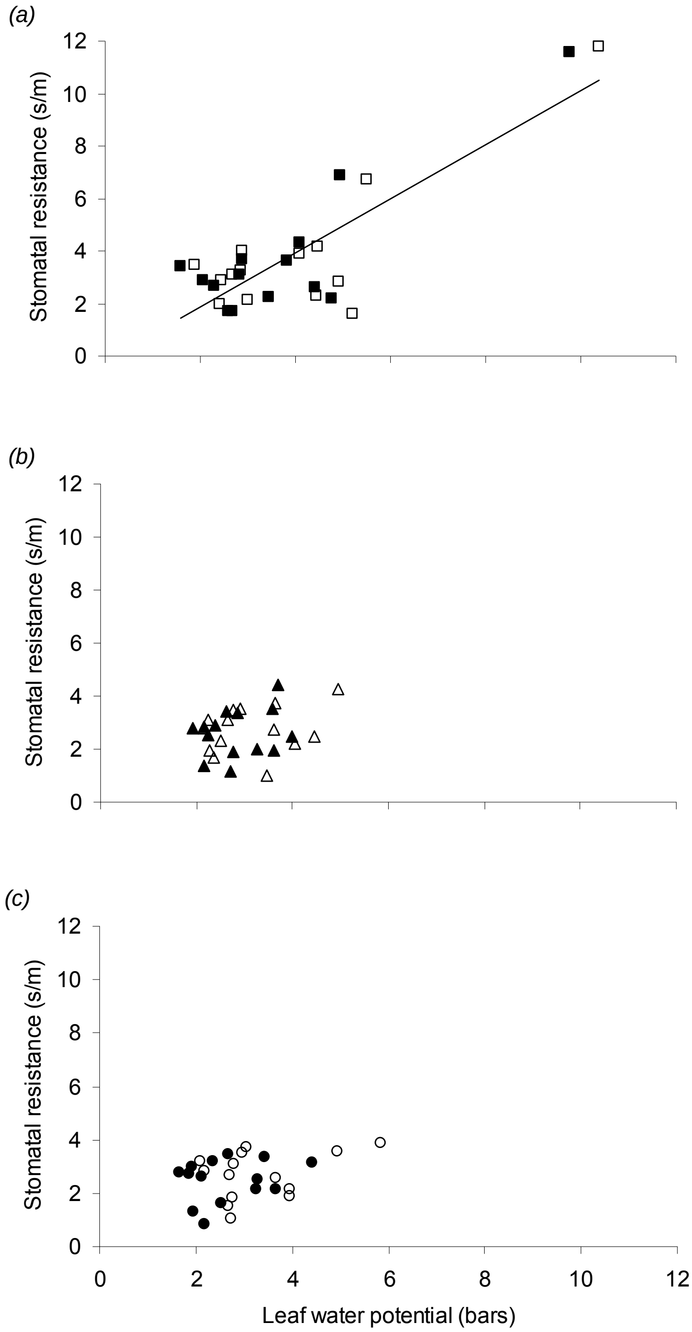

FIGURE 16. RELATIONSHIP BETWEEN STOMATAL RESISTANCE AND LEAF WATER POTENTIAL IN EXPT 2008. (A) UNIRRIGATED; (B) IRRIGATED; (C) OVER-IRRIGATED. CLOSED SYMBOLS UNSMEARED, OPEN SYMBOLS SMEARED. EQUATION OF LINE FOR UNIRRIGATED TREATMENTS, Y = 1.03X–0.21, R2 = 0.70. DATA ARE MEAN OF BOTH CLODDINESS TREATMENTS.

4.1.2.5. Number of stems and tubers and tuber fresh weight yields

When averaged over all treatments, the number of mainstems was c. 93 000/ha and this value was very consistent between samplings (Table 16). Neither irrigation nor soil conditions had any consistent, statistically significant effect on stem population. However, the number of mainstems was consistently reduced by c. 8 000/ha when the N application rate was increased from 0 to 200 kg N/ha. The number of tubers at the first harvest (29 days after emergence, DAE) was smaller than that found at subsequent harvests and this may be because some stems had only recently initiated and some tubers were still smaller than 10 mm. For all subsequent harvests, tuber populations were significantly larger in the Smeared soils than Unsmeared. At final harvest, the number of tubers > 10 mm was similar for all cultivations where no N was applied but with 200 kg N/ha there were more tubers from Smeared than Unsmeared treatments and this was associated with differences in the number of small (< 40 mm) tubers.

	24 June		21 July		26 August		24 September	
	Stems	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**
Unirrigated	90.6	425	90.2	490	89.8	478	94.1	496
Irrigated	94.4	429	94.3	510	95.8	504	91.3	489
Over-Irrigated	94.7	459	92.5	524	93.3	495	96.7	505
S.E. (33 D.F.)	2.28	14.2	2.40	11.9	2.45	12.3	2.69	10.4
Smeared	90.9	418	91.4	514	92.3	508	92.9	508
Unsmeared	95.6	458	93.2	502	93.6	477	95.2	485
S.E. (33 D.F.)	1.87	11.6	1.96	9.7	2.00	10.1	2.19	8.5
Fine tilth	93.1	435	93.1	510	93.8	499	93.4	497
Cloddy tilth	93.4	441	91.5	505	92.1	585	94.7	497
S.E. (33 D.F.)	1.87	11.6	1.96	9.7	2.00	10.1	2.19	8.5
0 kg N/ha	97.4	458	96.9	479	96.6	464	97.8	475
200 kg N/ha	89.1	418	87.7	537	89.4	521	90.2	518
S.E. (36 D.F.)	1.48	9.7	1.42	9.3	1.48	10.4	1.80	9.4

TABLE 16. MAIN EFFECT OF IRRIGATION, CULTIVATION AND N APPLICATION RATE ON NUMBER OF MAINSTEMS AND NUMBER OF TUBERS > 10 MM (000/HA) ON FOUR SAMPLING OCCASIONS IN EXPT 2008

Between the first and final harvests, average tuber FW yields increased from 5.3 to 66.6 t/ha (Table 17, Figure 17). At each harvest, tuber FW yields were significantly increased by irrigation and at the third and final harvests yields were also significantly greater in Over-irrigated treatments compared with Irrigated. Despite being grown in a season when evaporative demand was lower than average and rainfall plentiful, the Over-irrigated treatment increased yields by 4.8 t/ha when compared with Irrigated and 17.5 t/ha when compared with Unirrigated. The difference in yield between Over-irrigated and Irrigated treatments was not quite significant at final harvest but there was a trend at all harvests for Over-irrigated to have a higher yield than Irrigated. There were only short periods in June and July when the SMD in the Irrigated plots was close to or above the Limiting SMD (Figure 8), so it is surprising that yields were higher in Over-irrigated than Irrigated plots. A similar response to over-irrigation has previously been observed in the same field (Stalham & Gaze 2000). For all four harvests, the yields in Smeared soils were significantly smaller than those in Unsmeared soils and at final harvest the yields in the Smeared soils were c. 5 t/ha lower. In 2006, smeared soils decreased yield by c. 10 t/ha, whereas there was no difference in yield in 2007. At the first harvest, increasing the N application rate from 0 to 200 kg N/ha reduced tuber FW yield by c. 1.5 t/ha. This reduction in yield may have been a consequence of the effects of N on emergence but it is more likely that it was due to the effects of N on DM partitioning between haulm and tubers. At final harvest, where no N was applied tuber FW yields were c. 12 t/ha smaller than where 200 kg N/ha had been applied. Whether the crop was grown in a cloddy or in a fine-tilthed seedbed had no statistically significant effect on tuber FW yield at any harvest. The effects of irrigation and N application rate on tuber yields in Smeared and Unsmeared soils are shown in Table 18. When no N was applied, yields were reduced in Smeared soil, however, the yield penalty due to smearing was removed when 200 kg N/ha was applied. These data do not allow us to say whether crops grown in Smeared soils needed extra N to achieve their yield potential, however, they do show that in crops deficient in N (i.e. where no N was applied), the yield penalty was larger if soil conditions were poor. When no irrigation was applied, tuber yields in the Smeared and Unsmeared soils were similar. When irrigation was applied, yields were increased in crops grown in both Smeared and Unsmeared soil but the response to water was larger in the Unsmeared soil. The extra response may have been due to more extensive rooting in the Unsmeared soils and plants being able to make better use of the irrigation water (p. 38).

	24 June	21 July	26 August	24 September
Unirrigated	4.64	25.8	47.0	56.7
Irrigated	5.43	32.7	58.8	69.1
Over-irrigated	5.70	35.0	62.9	74.1
S.E. (33 D.F.)	0.229	0.78	1.24	1.71
Smeared	4.85	29.8	54.7	64.2
Unsmeared	5.66	32.5	57.7	68.8
S.E. (33 D.F.)	0.187	0.64	1.01	1.39
Fine tilth	5.30	31.1	56.3	66.6
Cloddy tilth	5.21	31.2	56.2	66.6
S.E. (33 D.F.)	0.187	0.64	1.01	1.39
0 kg N/ha	5.98	30.0	53.5	60.7
200 kg N/ha	4.53	32.3	58.9	72.5
S.E. (36 D.F.)	0.166	0.42	0.95	0.96

TABLE 17. MAIN EFFECTS OF CULTIVATION, IRRIGATION AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA) ON FOUR SAMPLING OCCASIONS IN EXPT 2008

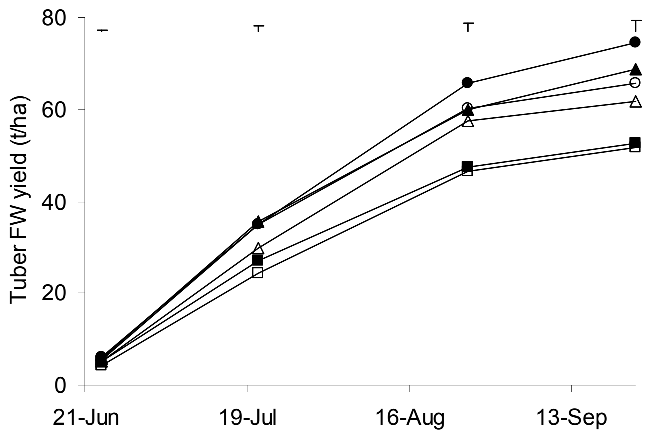

FIGURE 17. TUBER FW YIELD OVER TIME IN EXPT 2008. UNIRRIGATED, ■; IRRIGATED, ▲; OVER-IRRIGATED, ●; UNSMEARED, CLOSED SYMBOLS; SMEARED, OPEN SYMBOLS. DATA ARE MEANS OF BOTH CLODDINESS AND BOTH NITROGEN TREATMENTS. S.E. BASED ON 33 D.F.

	Smeared soil	Unsmeared soil	Mean
Unirrigated	56.5	56.9	56.7
Irrigated	66.2	72.0	69.1
Over-irrigated	70.0	78.1	74.1
S.E. (33 D.F.)	2.41		1.71
0 kg N/ha	55.8	65.7	60.7
200 kg N/ha	72.6	72.3	72.5
S.E. (36 D.F.)	1.69		0.96

TABLE 18. MAIN EFFECTS OF IRRIGATION AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA) IN SMEARED AND UNSMEARED SOIL AT FINAL HARVEST IN EXPT 2008

4.1.2.6. Total dry matter yield, radiation use efficiency and the onset of tuber bulking

The mean total dry matter (DM) yield at final harvest was 17.6 t DM/ha (
Table 19), with soil smearing reducing total DM yields by c. 1.2 t/ha whereas increasing the N application rate from 0 to 200 kg N/ha increased total DM yield by c. 2.7 t/ha. When compared with no irrigation, Over-irrigation increased total DM yield by c. 4 t/ha.

Whole-season radiation use efficiency (RUE) for each plot was estimated from the slopes of regression lines that fitted total DM yield against radiation absorption. The overall, average RUE for total DM production was 1.38 t DM/TJ and this value was very similar to the average found for a similar experiment in 2007 (1.36 t DM/TJ) but greater than in 2006 (1.13 t DM/TJ). Radiation use efficiency was increased by irrigating but was not affected by soil conditions or by N application rate. In conjunction with its effect on ground cover (Table 14), the increased RUE as a consequence of irrigating was also associated with the significant increase in total DM and tuber FW yield compared with Unirrigated plots. On average, the absorption of each TJ of energy was associated with the production of 1.30 t of tuber DM. The efficiency of tuber DM production was increased by irrigation but was not affected by either soil conditions or N application rate.

Ongoing studies in the USA and UK have shown that there is often a significant lag between tuber initiation (which typically occurs at 19-25 DAE) and the onset of the linear phase of tuber bulking and this lag is often associated with rapid, early season N uptake. The average interval between emergence and tuber bulking was 26 days (
Table 19) and the delay was increased when 200 kg N/ha was applied. However, this delay in the onset of tuber bulking was relatively small in relation to the potential length of the growing season and was unlikely to have had much effect on yield.

	Total DM yield 24 September (t DM/ha)	Radiation use efficiency total DM (t/TJ)	Radiation use efficiency tuber DM (t/TJ)	Onset of tuber bulking (DAE)
Unirrigated	15.3	1.26	1.20	26.8
Irrigated	18.1	1.40	1.32	26.1
Over-irrigated	19.4	1.46	1.39	26.0
S.E. (33 D.F.)	0.42	0.020	0.027	0.43
Smeared	17.0	1.37	1.31	25.9
Unsmeared	18.2	1.38	1.29	26.7
S.E. (33 D.F.)	0.34	0.016	0.022	0.35
Fine tilth	17.7	1.39	1.33	26.2
Cloddy tilth	17.5	1.36	1.28	26.3
S.E. (33 D.F.)	0.34	0.016	0.022	0.35
0 kg N/ha	16.2	1.38	1.33	25.2
200 kg N/ha	18.9	1.37	1.28	27.3
S.E. (36 D.F.)	0.29	0.013	0.018	0.46

TABLE 19. MAIN EFFECTS OF CULTIVATION, IRRIGATION AND N APPLICATION RATE ON TOTAL DM YIELD, RADIATION USE EFFICIENCY AND THE ONSET OF TUBER BULKING IN EXPT 2008

4.1.2.7. Tuber dry matter concentration

Tuber dry matter concentration, [DM], increased progressively during the season, however there were appreciable differences in the rate of increase of the three irrigation regimes during periods of high ET or drying soil. There was a linear increase in [DM] in Over-irrigated crops over the course of most of the season (Figure 18). However, [DM] in Unirrigated crops increased rapidly during early July and early August as a consequence of lack of rainfall and higher than average ET demand but within 2 weeks of both dry periods, tuber [DM] had fallen back to the same as Over-irrigated plots. A similar pattern was observed in Irrigated treatments, albeit the changes were smaller in magnitude than in Unirrigated and may indicate where tuber FW yield was lost in Irrigated compared with Over-irrigated treatments. There was a consistently higher [DM] in tubers grown in Smeared soil compared with Unsmeared, indicating that water movement into tubers was compromised by poor water uptake from compacted soil. This important effect has been observed in previous experiments involving soil compaction.

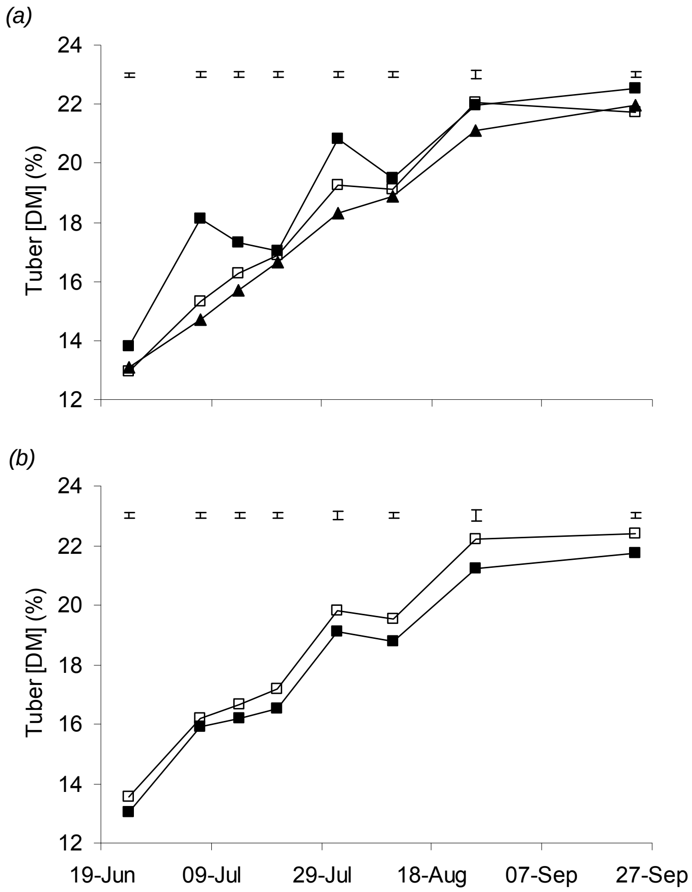

FIGURE 18. TUBER DRY MATTER CONCENTRATION [DM] IN EXPT 2008. (A) MAIN EFFECTS OF IRRIGATION, UNIRRIGATED, ■; IRRIGATED, □; OVER-IRRIGATED, ▲; (B) MAIN EFFECTS OF CULTIVATION REGIME, UNSMEARED, ■; SMEARED, □. S.E. BASED ON 33 D.F.

4.1.2.8. *Common scab and growth defects*

There was a very high incidence and severity of common scab in the experiment. There were no tubers with less than 1 % surface area infected with common scab and the mean incidence of tubers with ≤ 5 % surface area was only 7.5 ± 1.84 %. The mean severity (% surface area affected) of common scab was 25.8 ± 1.31 % and unaffected by any treatment including irrigation and the cloddiness of the ridge (Table 20). The first irrigation was applied on 19 June, 6 days after the onset of tuber initiation, by which time the SMD had increased to > 25 mm when it is recognised from other experiments at CUF that SMDs should be maintained c. 12mm to avoid common scab. The average SMD maintained during the 4 weeks after tuber initiation in Irrigated plots was 12.9 mm and there were 14 days during the susceptible period when the SMD exceeded the threshold for scab. In Unirrigated plots, the SMD averaged 35 mm over the susceptible period. The first Over-irrigation event in excess of Irrigated was only applied towards the end of the scab control period and, unsurprisingly, had no effect on common scab. The incidence of growth cracking was low (1.5 ± 0.44 %) and unaffected by irrigation, soil condition or N.

Irrigation	Cultivation	Cloddiness	Scab incidence < 5 % SA (%)	Ang.† scab incidence < 5 % SA	Scab severity (% SA)	Growth crack incidence (%)	Ang.† growth crack incidence
I-	Unsmeared	Cloddy	8.5	13.8	23.9	1.5	4.9
		Fine	13.6	17.5	27.7	0.5	2.0
	Smeared	Cloddy	11.0	18.9	22.9	1.0	4.1
		Fine	5.0	12.6	36.8	2.5	9.0
I	Unsmeared	Cloddy	2.8	6.6	28.6	2.9	10.1
		Fine	11.5	16.0	19.3	2.0	5.6
	Smeared	Cloddy	7.7	15.0	26.7	1.5	4.9
		Fine	9.0	17.1	22.1	1.5	3.5
I+	Unsmeared	Cloddy	0.5	2.0	27.8	2.5	7.8
		Fine	2.0	8.1	27.7	0.5	2.0
	Smeared	Cloddy	11.5	14.1	23.2	2.0	4.1
		Fine	7.5	13.3	23.4	0.0	0.0
		S.E. (33 D.F.)	-	4.94	3.20	-	2.76

†Angular transformation

TABLE 20. INCIDENCE AND SEVERITY (% SURFACE AREA, SA) OF COMMON SCAB AND INCIDENCE OF GROWTH CRACKING (200N TREATMENT ONLY) IN EXPT 2008

4.2. Experiment 2009a

4.2.1. Soil properties

4.2.1.1. Textural analysis

The average textural classification was a medium sandy clay loam but with areas of clay loam and sandy loam within the experimental area (Table 21). The average volumetric stone content (>2mm) taken from bulk density sampling was 5.5 ± 2.80 %.

	Sand			Silt	Clay	Textural
	Coarse	Medium	Fine			Classification
Block 1	1	54	11	19	15	Medium sandy loam
Block 2	1	46	12	22	19	Medium sandy clay loam
Block 3	1	42	10	26	21	Medium sandy clay loam
Mean	1	47	11	22	18	Medium sandy clay loam
S.E.		6.1	1.0	3.5	3.1	

TABLE 21. PROPORTIONS OF SAND, SILT AND CLAY (% GRAVIMETRIC) WITHIN THE EXPERIMENTAL AREA IN EXPT 2009A

4.2.1.2. Bulk density and porosity

In early-planted crops, bulk densities were only significantly different between cultivation regimes at a depth of 25-30 cm below the top of the ridge, which coincides with the rotavator depth working on a flat soil surface. Soil cultivated Moist had a lower bulk density at this depth than either Wet or Over-wet treatments (Figure 19a). For crops planted on 29 April, however, Wet or Over-wet cultivation regimes had significantly higher bulk density than Moist or Field Capacity throughout most of the profile, with the differences being considerable between 15 and 30 cm (Figure 19b). Total pore space showed the reverse trend to bulk density (Figure 20).

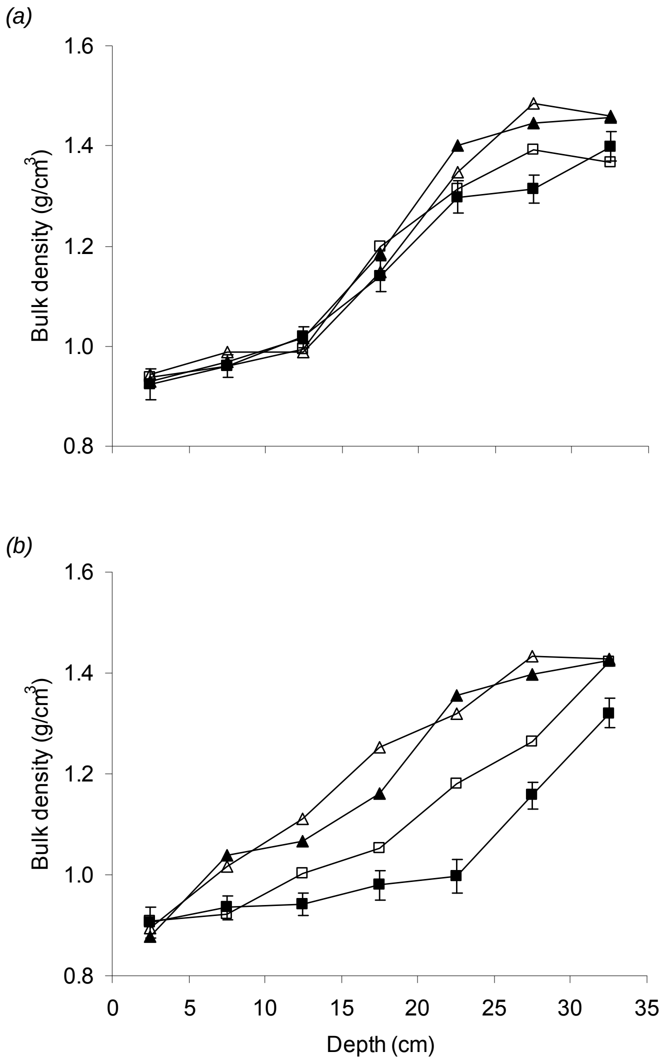

FIGURE 19. SOIL BULK DENSITY ON 7-10 AUGUST (A) 15 APRIL PLANTING; (B) 29 APRIL PLANTING IN EXPT 2009A. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E. BASED ON 30 D.F.

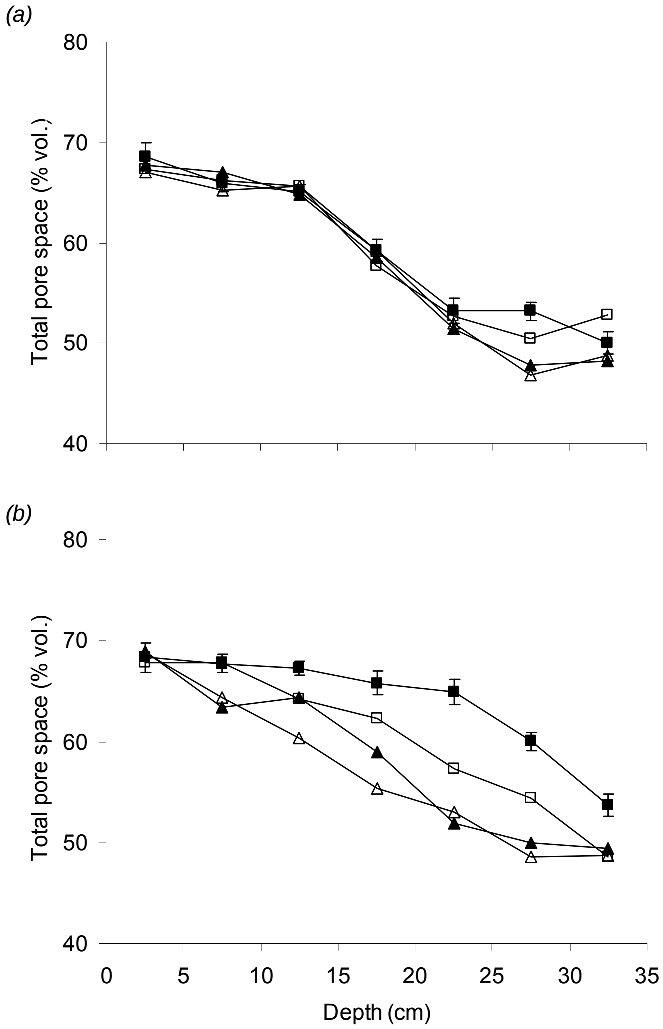

FIGURE 20. TOTAL PORE SPACE ON 7-10 AUGUST *(A)* 15 APRIL PLANTING; *(B)* 29 APRIL PLANTING IN EXPT 2009A. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E. BASED ON 30 D.F.

Plots cultivated 27-29 April had significantly higher bulk density in the ridge than those cultivated 7-8 April (Table 22). There was no significant effect of cultivation or irrigation regime on ridge bulk density.

	Cultivation regime			
	Moist	Field Capacity	Wet	Over-wet
15 April	1.14	1.17	1.16	1.19
29 April	1.20	1.23	1.21	1.19
S.E. (30 D.F.)	0.027			

TABLE 22. RIDGE BULK DENSITY (G/CM^3) ON 19 JUNE IN EXPT 2009A. DATA ARE MEANS OF BOTH IRRIGATION REGIMES

4.2.1.3. Resistance

Soil resistance immediately after planting was lower at 25 and 30 cm depths in Moist and Field Capacity treatments than in Wet and Over-Wet but was only significant at 30 cm in the early planting (Figure 21). The maximum resistance was c. 2.5 MPa. At the second measurement on 8 June, the soil was wet owing to rainfall and the resistance readings were similar to those taken at planting and there was no effect of irrigation regime (Figure 22).

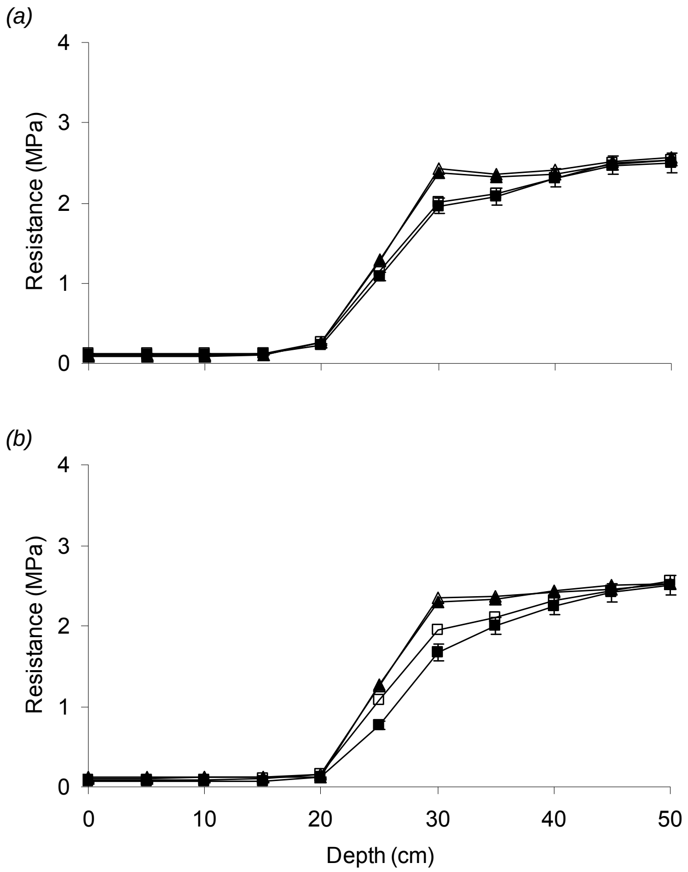

FIGURE 21. SOIL RESISTANCE AFTER PLANTING IN EXPT 2009A. *(A)* 15 APRIL PLANTING; *(B)* 29 APRIL PLANTING. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E. BASED ON 30 D.F. DATA ARE MEANS OF BOTH IRRIGATION REGIMES.

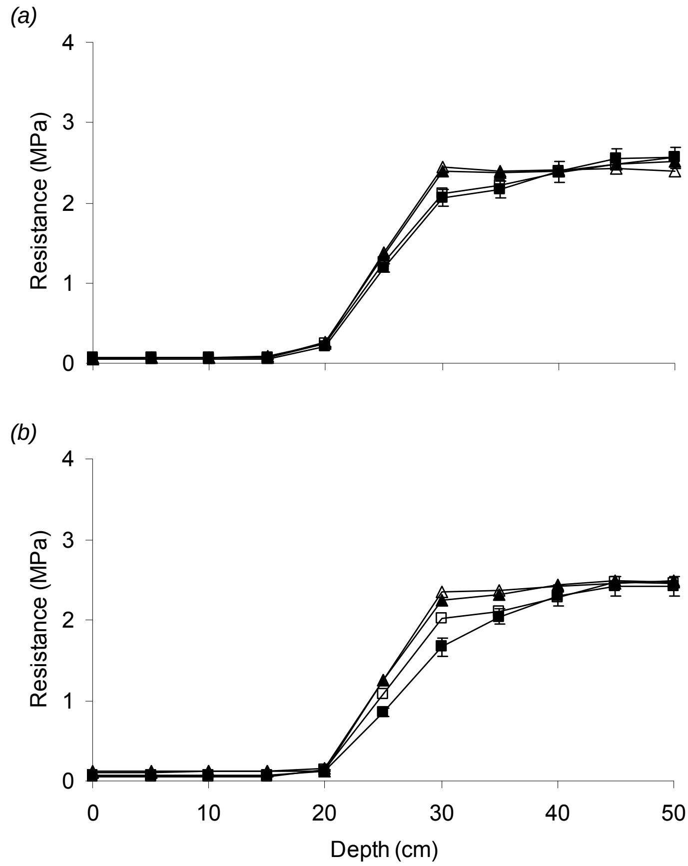

FIGURE 22. SOIL RESISTANCE ON 8 JUNE IN EXPT 2009A. *(A)* 15 APRIL PLANTING; *(B)* 29 APRIL PLANTING. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E. BASED ON 30 D.F. DATA ARE MEANS OF BOTH IRRIGATION REGIMES.

At the third measurement on 3 July, the soil was dry in Unirrigated plots (39-49 mm soil moisture deficit) and wetter in Irrigated plots (2-3 mm) and consequently the resistance was greater (Figure 23). There were only small differences in soil resistance between cultivation regimes in Irrigated plots but they kept the same relative values as at planting. However, in Unirrigated plots, the differences in resistance between cultivation regimes were much greater than observed at planting, showing that as soil dried its strength increased faster where the soil was more compacted. The maximum resistances measured in compacted, unirrigated soils were c. 3.7 MPa, comparable to those observed in Expt 2008 and a similar cultivation experiment in 2006.

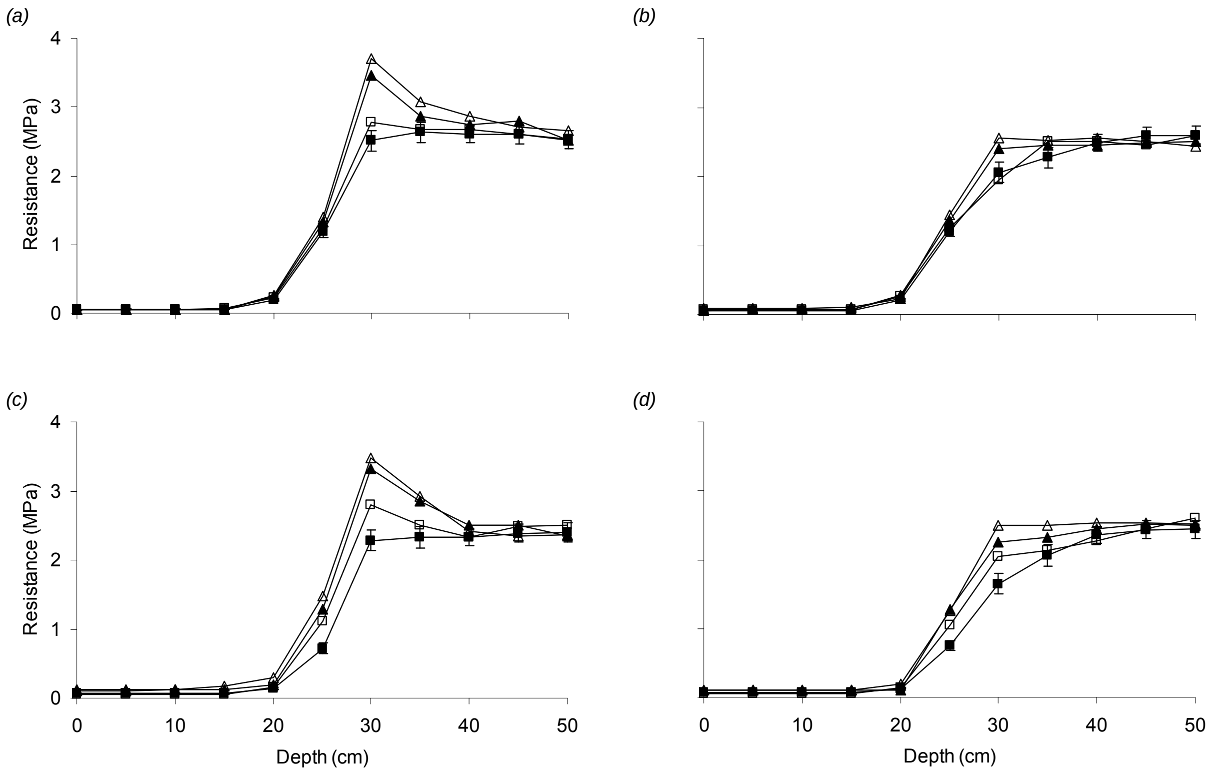

FIGURE 23. SOIL RESISTANCE ON 3 JULY IN EXPT 2009A. *(A)* 15 APRIL PLANTING UNIRRIGATED; *(B)* 15 APRIL PLANTING IRRIGATED; *(C)* 29 APRIL PLANTING UNIRRIGATED; *(D)* 29 APRIL PLANTING IRRIGATED. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E. BASED ON 30 D.F.

4.2.1.4. *Water holding capacity*

Soil water holding capacity on a gravimetric basis was not significantly affected by any treatment but owing to differences in bulk density between cultivation treatments there was significantly less water held at low soil water tensions on a volumetric basis when soil was cultivated Moist rather than Wet or Over-wet, particularly for the later planting (Table 23)). The compression of wetter soil during cultivation reduced the volume of large pores but increased the amount of water available to plants. Access to this ‘extra’ water depends on rooting density within these higher density soil horizons.

Depth (cm)	**15-20**		**25-30**	
Water potential (bar)	**0.6**	**2.0**	**0.6**	**2.0**
15 April				
Moist	20.0	18.8	24.0	22.8
Field Capacity	19.1	18.1	23.3	22.2
Wet	23.3	21.5	28.7	27.9
Over-wet	24.7	22.5	29.2	27.8
29 April				
Moist	15.4	13.8	18.3	17.2
Field Capacity	17.5	16.5	22.5	21.3
Wet	24.1	22.8	27.3	24.5
Over-wet	23.3	22.2	26.7	23.5
S.E. (30 D.F.)	1.55	1.51	1.74	1.70

TABLE 23. AVAILABLE WATER HOLDING CAPACITY (% VOLUMETRIC) IN EXPT 2009A. DATA ARE MEANS OF BOTH IRRIGATION REGIMES

4.2.1.5. Ped size distribution

Irrigation regime had no significant effect on ped size distribution. Allowing the soil to dry between plantings resulted in a smaller mean ped size for the 15 April planting than 29 April, except for the Moist regime where mean ped size was similar between plantings (Table 24)

	Cultivation regime			
	Moist	Field Capacity	Wet	Over-wet
15 April	12.4	10.2	11.1	13.0
29 April	12.2	12.9	13.5	14.4
S.E. (30 D.F.)	0.85			

TABLE 24. MEAN PED SIZE (MM) ON 19 JUNE IN EXPT 2009A. VALUES ARE MEANS OF BOTH IRRIGATION REGIMES

The distribution of ped sizes was largely unaffected by cultivation regime. There were more very large peds (> 45 mm) in the later planting than the early but the converse was generally true with peds < 15 mm diameter (Figure 24). With respect to very fine peds (< 2 mm), there were greater proportions of these in Field Capacity treatments than in Moist and Over-wet.

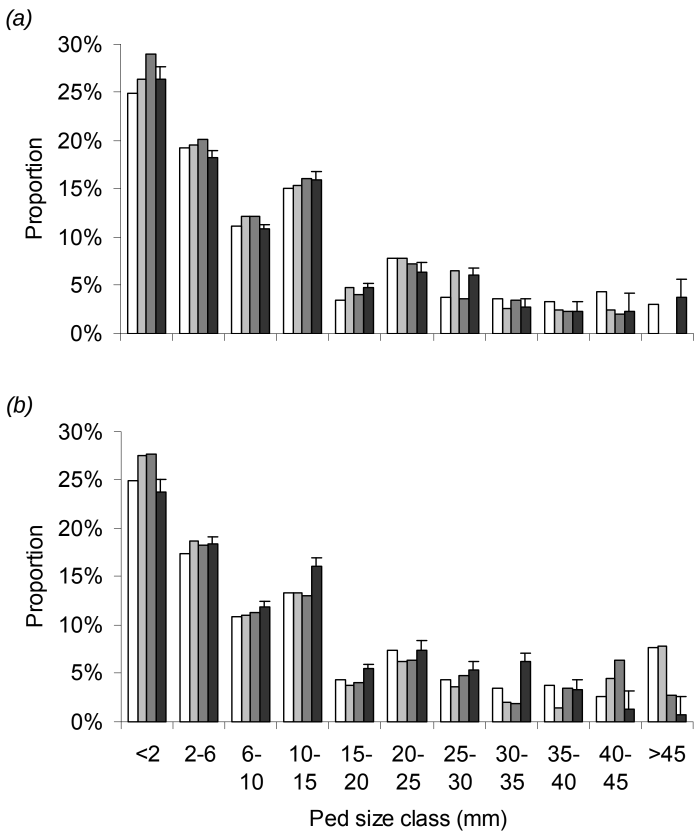

FIGURE 24. PED SIZE DISTRIBUTION FOR (A) 15 APRIL AND (B) 29 APRIL PLANTING IN EXPT 2009A. MOIST, ■; FIELD CAPACITY, ■; WET, ■; OVER-WET, □. DATA ARE MEANS OF BOTH IRRIGATION REGIMES. S.E. BASED ON 30 D.F.

4.2.2. Plant measurements

4.2.2.1. Emergence, ground cover and radiation absorption

The average date of 50 % plant emergence was 23 May (27 days after planting) for the first planting and 1 June (22 days after planting) for the second planting. For the first planting, increasing the soil moisture content when the soil was cultivated delayed crop emergence by c. 4 days but this effect was not seen at the second planting, although at the later planting the Moist cultivation regime was c. 3 days slower to reach 50 % emergence than other cultivation regimes owing to dry soil at seed depth. All plots achieved complete or near-complete emergence. The effects of the treatment combinations on ground cover development are shown in Figure 25 and key data on ground cover development and radiation absorption are shown in Table 25.. The average rate of ground cover expansion (between 40 and 60 % ground cover) was 4.7 %/day. In a similar experiment in 2008, the average rate of ground cover expansion was 3.4 % day suggesting that in 2009 environmental conditions were better. This analysis also showed that the rate of expansion was faster for the later-planted plots and in crops that had received irrigation when compared with Unirrigated. All plots achieved 100 % ground cover. Canopy senescence started in late August. On average, the canopies of the Unirrigated crops maintained complete ground cover for c. 7 days longer than Irrigated crops and at final harvest (28 September) the average ground cover of the Unirrigated crops was 63 % compared with 48 % in the Irrigated crops. The average, season long-integrated ground cover was 9347 % days and this was not significantly affected by any treatment. On average, the 2009 crop was more persistent than the 2008 crop, which averaged 8927 % days. Radiation absorption averaged 14.51 TJ/ha (13.16 TJ/ha in 2008) and the effects of treatments on radiation absorption were small and statistically non-significant.

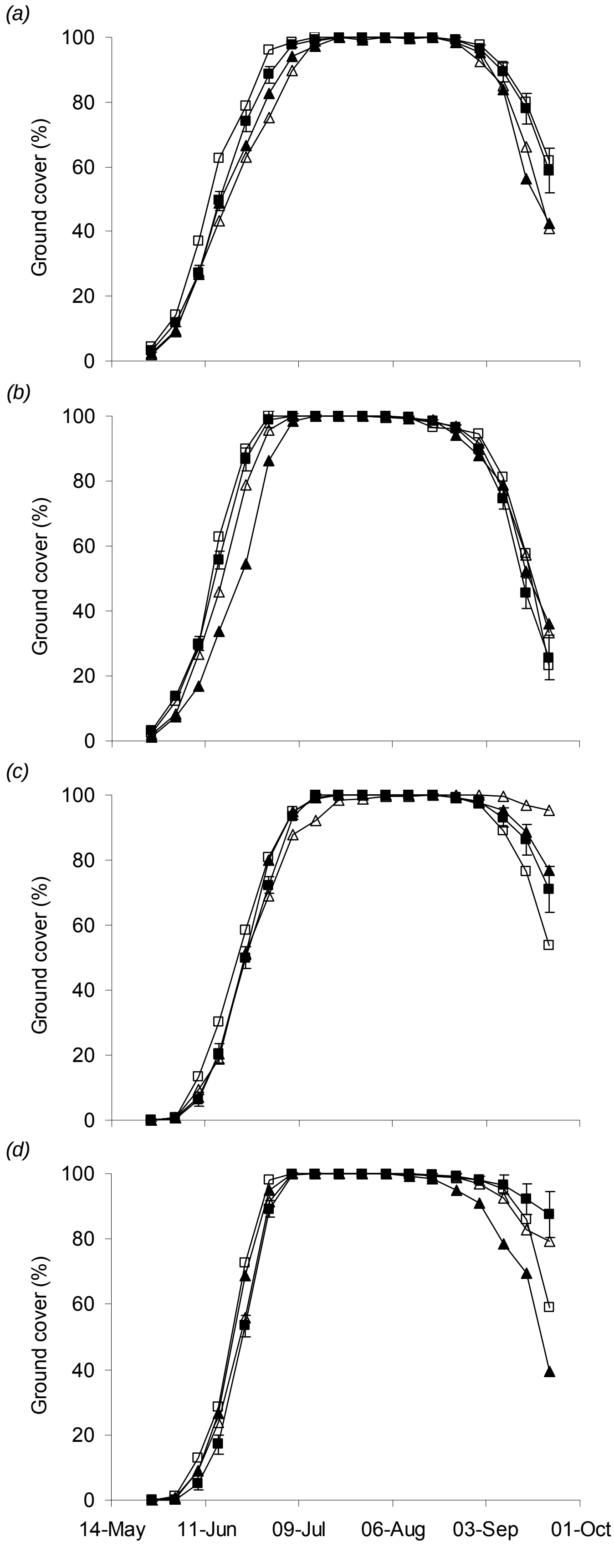

FIGURE 25. EFFECT OF SOIL MOISTURE CONTENT AT CULTIVATION ON GROUND COVER DEVELOPMENT IN EXPT 2009A. (A) 15 APRIL UNIRRIGATED; (B) 15 APRIL IRRIGATED; (C) 29 APRIL UNIRRIGATED; (D) 29 APRIL IRRIGATED. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E. BASED ON 30 D.F.

		Rate of ground cover increase (%/day)	Integrated ground cover (% days)	Radiation absorption (TJ/ha)
Planting date	15 April	4.31	9379	14.74
	29 April	5.09	9394	14.28
	S.E. (30 D.F.)	0.135	117.8	0.164
Soil cultivation regime	Moist	4.89	9489	14.62
	Field Capacity	4.89	9589	14.95
	Wet	4.61	9110	14.10
	Over-wet	4.43	9359	14.36
	S.E. (30 D.F.)	0.191	166.6	0.232
Irrigation regime	Unirrigated	4.02	9450	14.49
	Irrigated	5.38	9324	14.53
	S.E. (30 D.F.)	0.135	117.8	0.164

TABLE 25. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON MAXIMUM GROUND COVER, RATE OF INCREASE (BETWEEN 40 AND 60 % GROUND COVER), SEASON-LONG INTEGRATED GROUND COVER AND RADIATION ABSORPTION IN EXPT 2009A

4.2.2.2. Rooting density

Root length density was only examined in the soil horizons where there were significant differences in soil bulk density (20-25, 25-30 and 30-35 cm depths). In general, root length density was similar to that found in 2008, with a large decrease below 25 cm deep (Figure 26). Root length density was not significantly different between cultivation regimes at 20-25 cm but deeper in the profile there was a reduction in root length density in soils cultivated Wet or Over-wet compared with Moist or Field Capacity. The effect was only significant at the later planting although the same trend was apparent for the 15 April planting. As found previously (Stalham & Allen 2001), keeping soils wet through irrigation increased RLD in the 20-35 cm horizon compared with Unirrigated soils (Figure 26). There was a larger decrease (24 %) in rooting density between Moist and Wet or Over-wet cultivation regimes than increase in bulk density (11 %) between these treatments. Water holding capacity in the 25-35 cm profiles was 32 % greater in Wet and Over-wet cultivation regimes than the Moist cultivation regime which would compensate for much of this decrease in root length density.

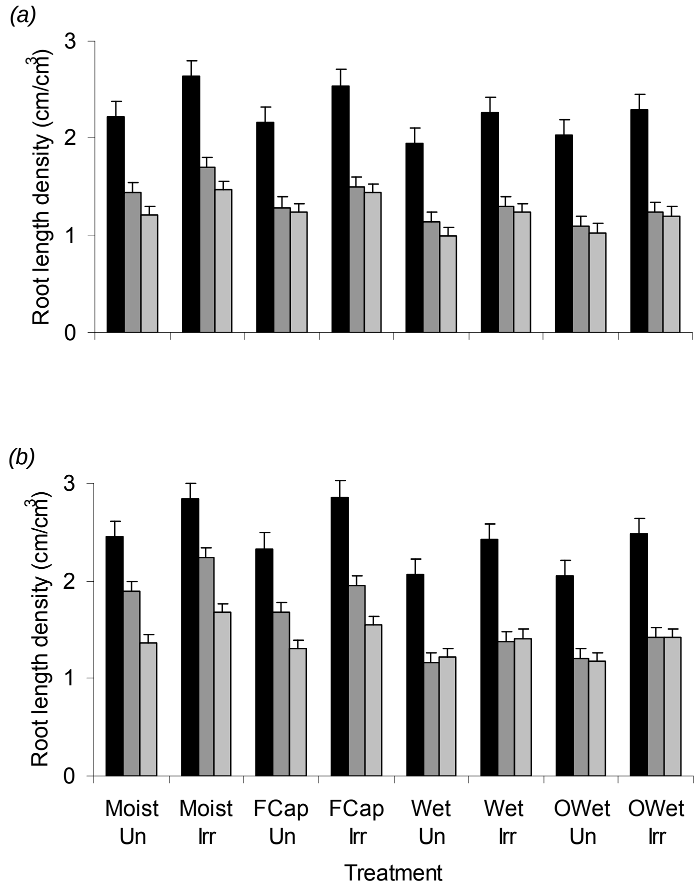

FIGURE 26. ROOT LENGTH DENSITY ON 7-10 AUGUST IN EXPT 2009A. (A) 15 APRIL PLANTING; (B) 29 APRIL PLANTING. DEPTHS: 20-25 CM, ■; 25-30 CM, ■; 30-35 CM, ■. KEY: MOIST UN, CULTIVATED MOIST UNIRRIGATED; MOIST IRR, CULTIVATED MOIST IRRIGATED; FCAP UN, CULTIVATED FIELD CAPACITY UNIRRIGATED; FCAP IRR, CULTIVATED FIELD CAPACITY UNIRRIGATED; WET UN, CULTIVATED WET UNIRRIGATED; WET IRR, CULTIVATED WET IRRIGATED; OWET UN, CULTIVATED OVER-WET UNIRRIGATED; OWET IRR, CULTIVATED OVER-WET IRRIGATED. S.E. BASED ON 30 D.F.

4.2.2.3. Stomatal resistance

On 23 June canopies were incomplete (early planting 74-90 % ground cover, late planting 50-73 %), ET0 was moderately high at 4.57 mm and it had been hot, sunny and with no significant rain for the 2 previous weeks. Crops started the day with moderate-low stomatal resistances in Unirrigated crops (2.7 s/cm) and low resistances in Irrigated (1.9). Resistance increased slowly throughout the day in Unirrigated crops but there was a faster increase between 14 and 16:00 h in Wet and Over-wet cultivation regimes (Figure 27a, c) so that they ended the day with higher resistances (6-7 s/cm) than Moist and Field Capacity regimes (4-5 s/cm). In Irrigated crops, there was no change in resistance during most of the day but resistances increased between 14:00 and 16:00 h, though not to the same extent as in Unirrigated crops (Figure 27b, d). There was a trend for crops grown in soil cultivated Wet and Over-wet to have higher resistances than drier soil but the differences were not significant. There was a similar response in both early and late plantings.

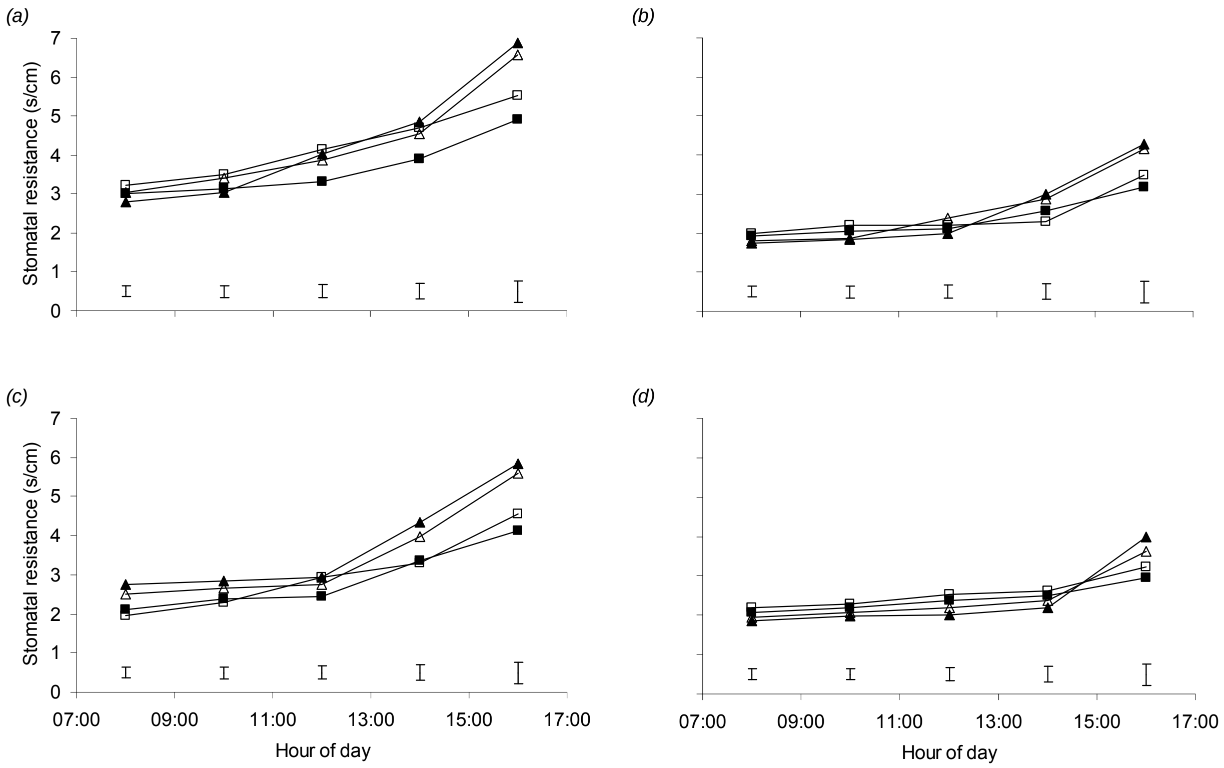

FIGURE 27. STOMATAL RESISTANCE ON 23 JUNE IN (A) 15 APRIL PLANTING UNIRRIGATED; (B) 15 APRIL PLANTING IRRIGATED; (C) 29 APRIL PLANTING UNIRRIGATED; (D) 29 APRIL PLANTING IRRIGATED IN EXPT 2009A. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E.S BASED ON 30 D.F.

The resistances measured on 30 June when there was high evaporative demand, (5.25 mm) are shown in Figure 28. Unirrigated crops commenced the day with slightly higher stomatal resistances (1.7 s/cm) than Irrigated (1.3) and the resistance increased throughout the day, with a larger increase between 14:00 and 16:00 h in Wet and Over-wet cultivation regimes than in Moist and Field Capacity. In Irrigated crops, there was a significant increase in resistance between 14:00 and 16:00 h in Wet and Over-wet cultivation regimes for early-planted crops that was not apparent for Moist and Field Capacity cultivation regimes. For later-planted Irrigated crops, resistance barely altered during the course of the day and all cultivation regimes had similar resistances. On average, there was no difference in resistance between planting dates.

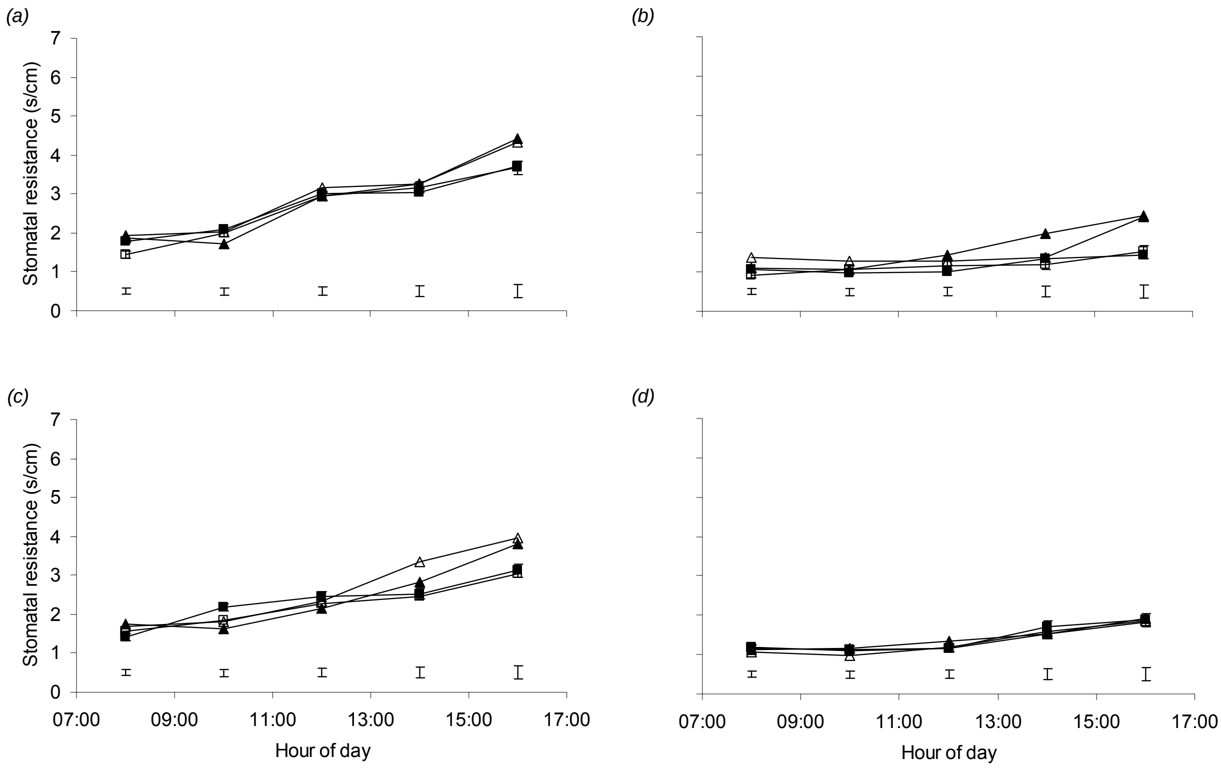

FIGURE 28. STOMATAL RESISTANCE ON 30 JUNE IN (A) 15 APRIL PLANTING UNIRRIGATED; (B) 15 APRIL PLANTING IRRIGATED; (C) 29 APRIL PLANTING UNIRRIGATED; (D) 29 APRIL PLANTING IRRIGATED IN EXPT 2009A. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E.S BASED ON 30 D.F.

Approximately 2 weeks later when all canopies were complete, frequent measurements of stomatal resistance were taken on a day when ET0 was more moderate (3.72 mm) than on 30 June, and the results are shown in Figure 29. Both Unirrigated and Irrigated crops started the measurement period with a stomatal resistance of 2.1 s/m. Resistance increased steadily from 10:00 h in Unirrigated crops (Figure 29a, c) but there was no significant difference in resistance across cultivation regime for early planting, whilst for later planting Moist and Field Capacity cultivation treatments had lower resistance than Wet and Over-wet from mid-afternoon onwards. In Irrigated crops, there was little change in resistance during the course of the day for any cultivation regime but by 16:00 h there was a significantly greater resistance for Wet and Over-wet treatments than for Moist and Field Capacity in early plantings (Figure 29b), albeit the differences were small compared with the changes in resistance during the day in Unirrigated crops.

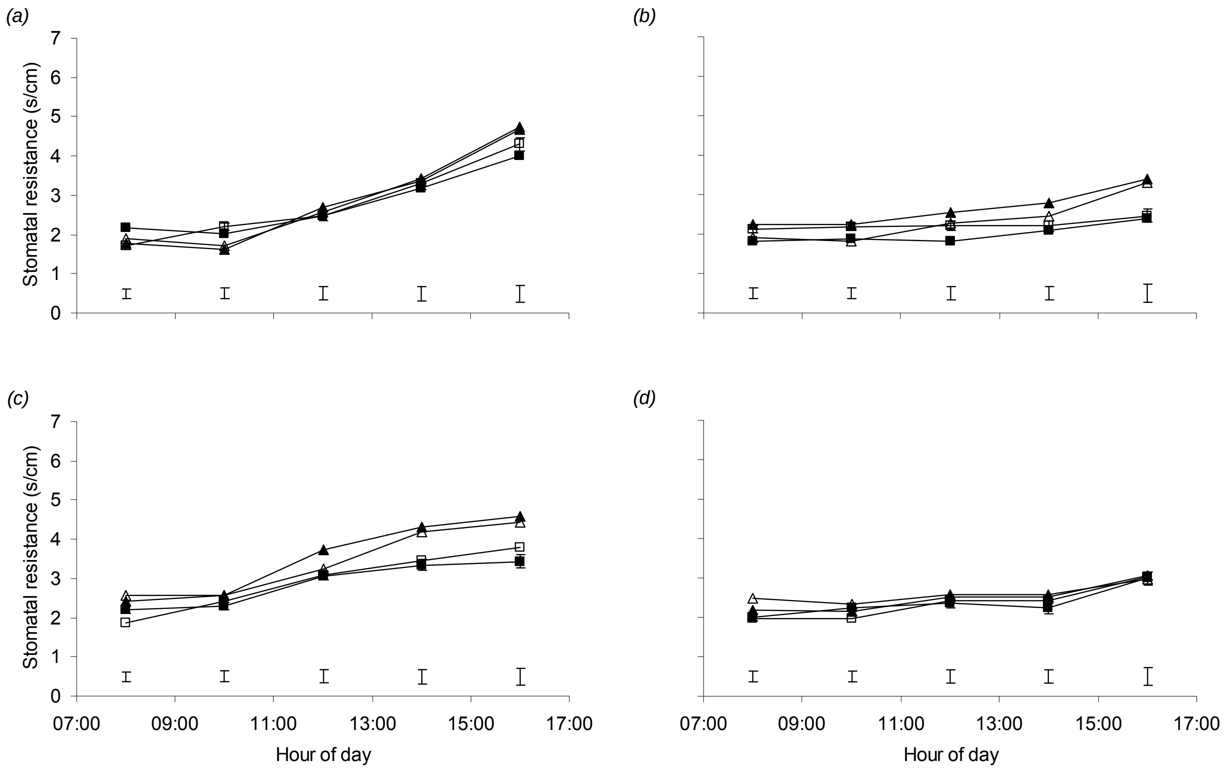

FIGURE 29. STOMATAL RESISTANCE ON 16 JULY IN (A) 15 APRIL PLANTING UNIRRIGATED; (B) 15 APRIL PLANTING IRRIGATED; (C) 29 APRIL PLANTING UNIRRIGATED; (D) 29 APRIL PLANTING IRRIGATED IN EXPT 2009A. SOIL CULTIVATION REGIME: MOIST, ■; FIELD CAPACITY □; WET, ▲; OVER-WET, △. S.E.S BASED ON 30 D.F.

In summary, Unirrigated crops showed larger changes in stomatal resistance throughout the day (c. 2.2 s/cm) than Irrigated (0.6-1.6 s/cm) and even though the ET0 demand varied from 3.7-5.3 mm/day, this had no effect on the magnitude of the change in resistance in Unirrigated crops. In Irrigated crops, the largest increase in stomatal resistance was when canopies were incomplete and ET was moderate-high (23 June) but otherwise there were only small changes during the day suggesting the soil was kept at a water content sufficient to maintain plant water balance, transpiration and growth. The trend across all treatments was for stomatal resistance to increase most rapidly between 14:00 and 16:00 h and for Wet and Over-wet cultivation regimes to have greater resistances at 16:00 h than Moist and Field Capacity.

4.2.2.4. *Leaf and tuber water potential*

Leaf and tuber water potential were measured at 2 hour intervals in Moist and Over-wet cultivation regimes only on two occasions, 30 June and 16 July. On 30 June, leaf water potentials were initially similar (0.9-1.6 bars) for all treatments monitored and increased rapidly in Unirrigated crops between 09:00 and 13:00 h in early-planted crops but continued to increase in late-planted crops until 15:00 h (Figure 30a, b). Leaf water potentials decreased between 15:00 and 17:00 h, more in late-planted than early-planted crops. Leaf water potentials in Irrigated crops increased more slowly than Unirrigated and reached a peak between 13:00 and 15:00 h but did not decrease towards the end of the day like Unirrigated crops. There was a trend for crops growing in soil cultivated at a higher water content to have higher leaf water potentials than those cultivated in drier soil but the difference was not significant at every sampling time.

The increase in the water potentials of tubers lagged behind that of leaves and generally reached a peak at the end of the day, except in late-planted, Unirrigated crops where the water potential was highest around 15:00 h (Figure 30c, d). Peak tuber water potentials were c. 3 bars in Unirrigated crops compared with c. 5-6 bars in the leaves of the same crops. Irrigated crops had peak tuber water potentials of 1.7 bars compared with 2.4 bars in leaves. As with leaf water potentials, there was a trend for crops growing in soil cultivated at a higher water content to have higher tuber water potentials but the difference was not significant at every sampling time.
Temperatures continued to increase to 17:00 h on 30 June, reaching a peak of 29 °C, whilst incident radiation and ET0 peaked at 14:00 h (Figure 31a). The patterns of decreasing leaf water potential between 15:00 and 17:00 h therefore appeared to follow the decreasing intensity of radiation and evaporative demand rather than temperature.

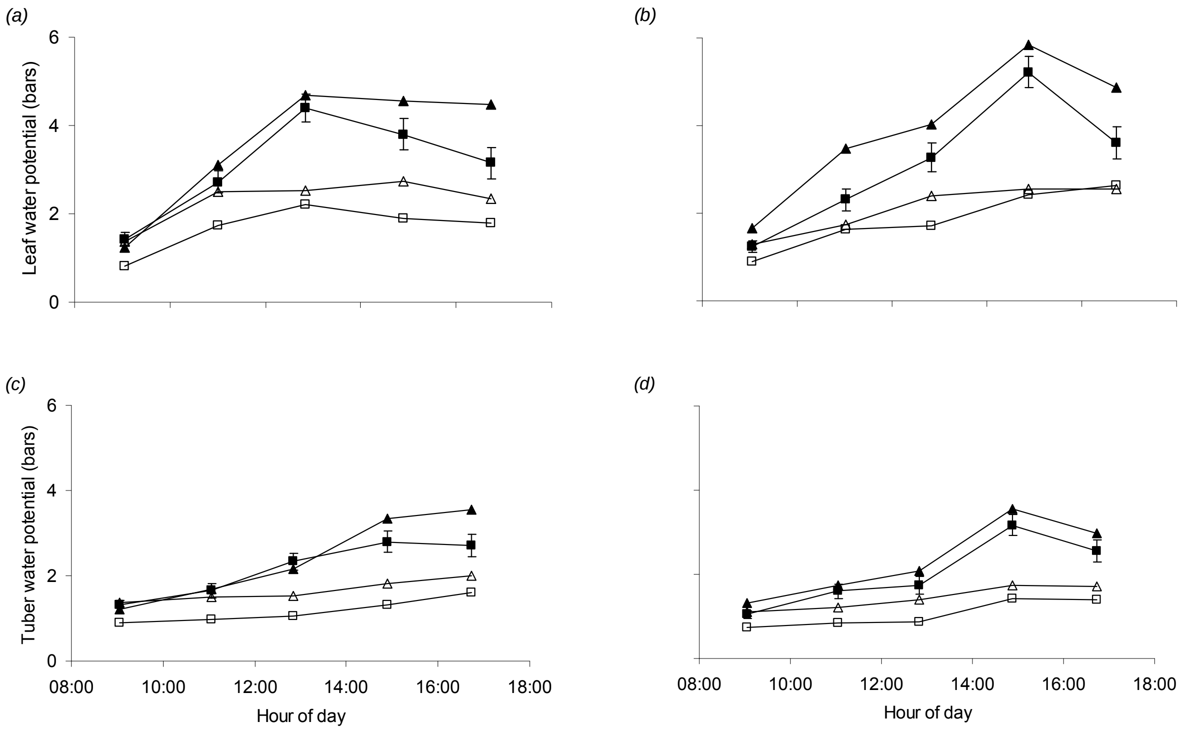

FIGURE 30. LEAF AND TUBER WATER POTENTIAL ON 30 JUNE IN EXPT 2009A. (A) LEAF 15 APRIL PLANTING; (B) LEAF 29 APRIL PLANTING; (C) TUBER 15 APRIL PLANTING; (D) TUBER 29 APRIL PLANTING. SOIL CULTIVATION REGIME: MOIST UNIRRIGATED, ■; MOIST IRRIGATED □; OVER-WET UNIRRIGATED, ▲; OVER-WET IRRIGATED, △. S.E.S BASED ON 14 D.F.

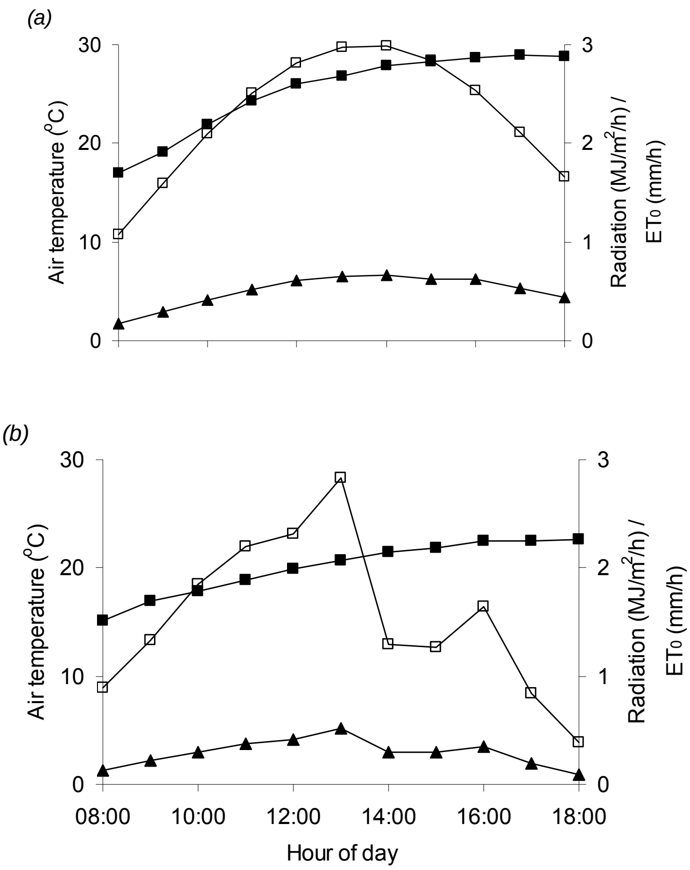

FIGURE 31. AIR TEMPERATURE (■), RADIATION (□) AND EVAPOTRANSPIRATION (ET_0, ▲) ON *(A)* 30 JUNE; *(B)* 16 JULY IN EXPT 2009A

On 16 July, leaf water potentials at the start of the day were higher in Unirrigated crops (mean 3.1 bars) than Irrigated (1.5) and increased rapidly to a peak between 11:00 and 13:00 h (Figure 32a, b). Thereafter, leaf water potential decreased towards the end of the day. Whilst there were fluctuations in water potential during the day, the leaves returned to similar water potentials by 17:00 h as at the start of the day. The pattern of changes in tuber water potential was similar to those of the leaves but the changes were smaller (Figure 32c, d). The tubers, however, ended the day at slightly higher water potential than they started. Similar to the readings taken on 30 June, there was a trend for crops growing in soil cultivated at a higher water content to have higher leaf and tuber water potentials but the differences were smaller in Irrigated crops than Unirrigated.

The patterns of temperature, radiation and ET0 were different to 30 June. It was cooler during the morning and at 13:00 h radiation intensity and ET0 decreased dramatically (Figure 31b) as cloud cover increased, which was reflected in the re-hydration of both leaves and tubers in Unirrigated crops during the afternoon.

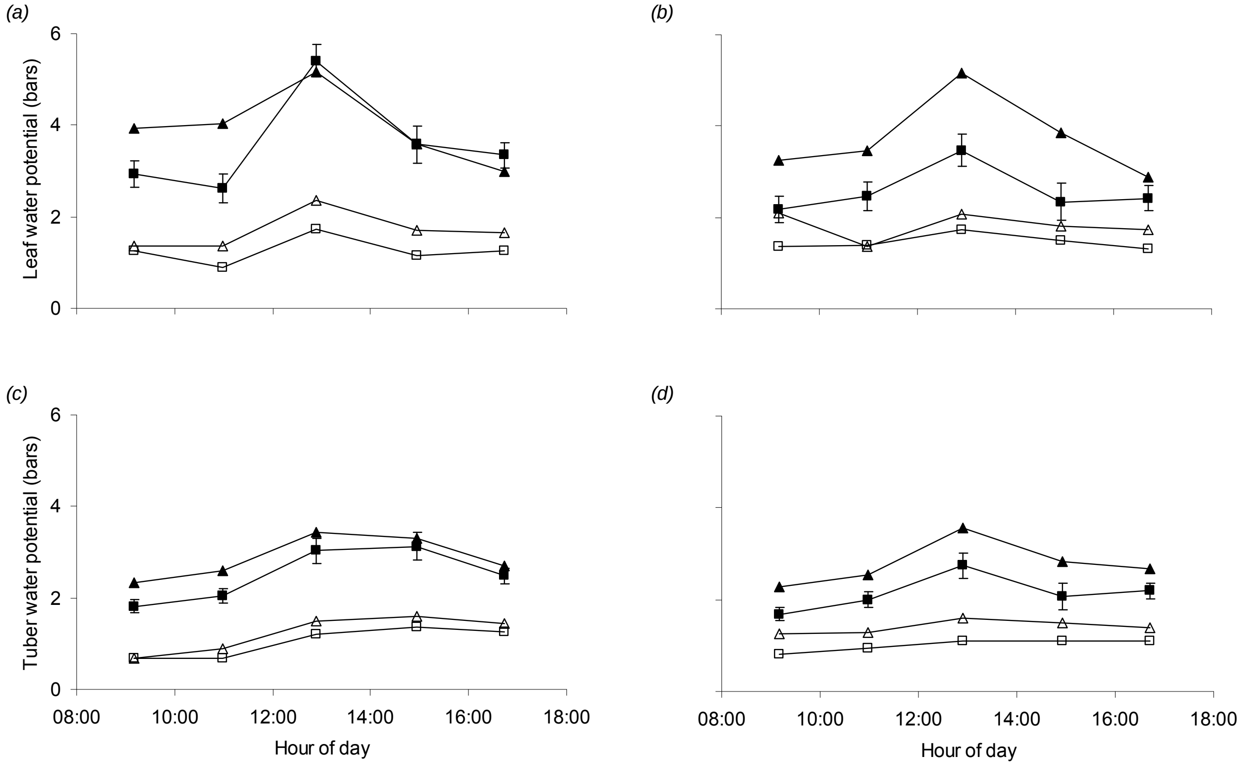

FIGURE 32. LEAF AND TUBER WATER POTENTIAL ON 16 JULY IN EXPT 2009A. (A) LEAF 15 APRIL PLANTING; (B) LEAF 29 APRIL PLANTING; (C) TUBER 15 APRIL PLANTING; (D) TUBER 29 APRIL PLANTING. SOIL CULTIVATION REGIME: MOIST UNIRRIGATED, ■; MOIST IRRIGATED □; OVER-WET UNIRRIGATED, ▲; OVER-WET IRRIGATED, △. S.E.S BASED ON 14 D.F.

Work from Gandar & Tanner (1976) and previous work at CUF in 2006-2007 suggested that tubers can act as a reservoir of water for maintaining leaf water potential. As leaves dehydrated during the day, the water potential in tubers also subsequently increased, with the time lag being dependent on the stage of hydration of leaves at the beginning of each day. In unirrigated crops where the SMD was high, increases in leaf water potential were quickly followed by increases in tuber water potential, whereas in irrigated crops where the SMD was low, leaves appeared to have to reach a threshold water potential before dehydration of tubers began. The extent of the dehydration of tubers during the day is also dependent on the magnitude of the evaporative demand on the canopy and on cool, dull days, little dehydration of tubers is observed whereas on hot, sunny days the difference in hydration status between morning and evening can be great and tuber water potentials in dry soils can attain those reached by leaves. During late afternoon and overnight, crops re-hydrate both leaves and tubers, the extent of which depends on soil wetness. Gandar & Tanner (1976) found that tubers gradually dehydrated over repeated daily drying cycles so that tubers eventually started the day at similar water potentials to leaves (c. 2.5 bar).

At 08:00 h on 30 June, leaves and tubers had similar water potentials in early-planted crops, whereas tubers had lower water potentials than leaves in late-planted crops (Figure 33a, b). The ratio between tuber : leaf water potential decreased similarly in all early-planted crops down to a ratio of c. 0.5 at 13:00 h, and then increased again until by 17:00 h all irrigation and cultivation treatments had a ratio of 0.85 (Figure 33a). In late-planted crops, the ratio of tuber : leaf water potential was similar across all treatments with the exception of the readings taken at 11:00 h but by the end of the day the ratio was lower (0.63) than for early-plantings (Figure 33b).

On 16 July, tubers commenced the day with considerably lower water potential (1.44 bar) than leaves (2.30), a ratio of 0.6. Generally, only small differences in the ratio of tuber : leaf water potential were measured during the day and, on average, irrigation and cultivation treatments had no significant effects on this ratio (Figure 33c, d). The ratio of tuber : leaf water potential in early-planted crops ended the day, on average, slightly higher than the start (Figure 33c), whereas in late-planted crops there was less difference between 09:00 and 17:00 h (Figure 33d).

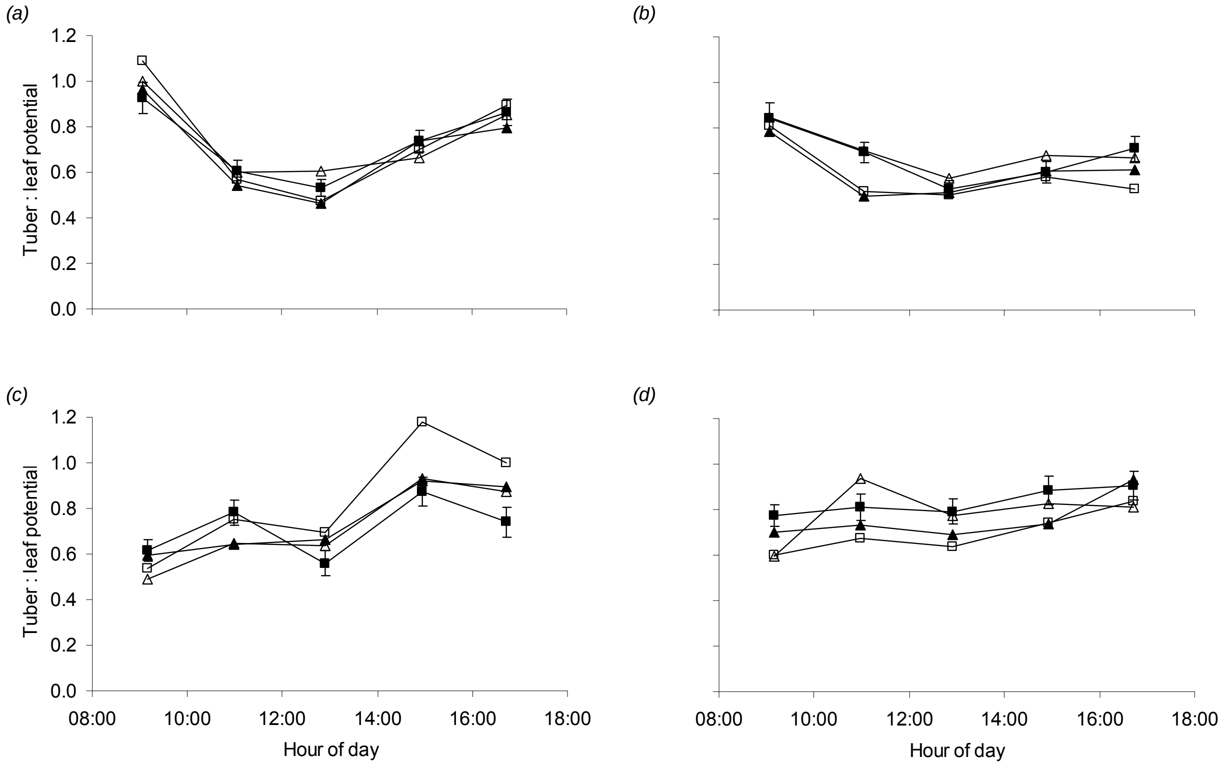

FIGURE 33. RATIO OF TUBER : LEAF WATER POTENTIAL ON (A) 30 JUNE, 15 APRIL PLANTING; (B) 30 JUNE, 29 APRIL PLANTING; (C) 16 JULY, 15 APRIL PLANTING; (D) 16 JULY, 29 APRIL PLANTING IN EXPT 2009A. SOIL CULTIVATION REGIME: MOIST UNIRRIGATED, ■; MOIST IRRIGATED □; OVER-WET UNIRRIGATED, ▲; OVER-WET IRRIGATED, △. S.E.S BASED ON 14 D.F.

4.2.2.5. Number of stems and tubers, tuber fresh weight yield and dry matter concentration

When averaged over all treatment combinations, the number of mainstems was 135 000/ha and this value was consistent between samplings (Table 26). The effects of soil water content at cultivation or irrigation on stem population were generally small but the later planting had more stems than the earlier planting (on average 17 000 stems/ha more) consistent with an increase in seed age between planting. For both planting dates the first sampling was done whilst the tuber population was still increasing and there were few tubers > 10 mm. At the second and subsequent harvests, numbers of tubers > 10 mm were greater for the later planting than the earlier planting and greater for the Irrigated than the Unirrigated crops. Effects of soil water content at cultivation on tuber population were small and inconsistent.

		19 or 23 June		17 July		6 August		28 September	
		Stems	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**	**Stems**	**Tubers**
Date of planting	15 April	126	221	129	453	124	476	125	509
	29 April	145	215	141	521	142	564	143	567
	S.E. (30 D.F.)	3.1	27.2	3.2	14.9	2.7	12.1	3.3	11.8
Soil cultivation regime	Moist	132	213	134	494	132	535	128	549
	Field Capacity	144	277	128	501	138	550	137	532
	Wet	130	205	143	491	128	496	138	529
	Over-wet	136	178	136	463	134	499	134	541
	S.E. (30 D.F.)	4.4	38.5	4.5	21.1	3.8	17.2	4.6	16.6
Irrigation regime	Unirrigated	137	244	138	453	136	486	134	512
	Irrigated	135	192	132	521	130	554	134	564
	S.E. (30 D.F.)	3.1	27.2	3.2	14.9	2.7	12.1	3.3	11.8

TABLE 26. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON NUMBER OF MAINSTEMS (000/HA) AND NUMBER OF TUBERS > 10 MM (000/HA) IN EXPT 2009A

At the second sampling tuber fresh weight yields were significantly larger for crops that had received irrigation than Unirrigated crops and for crops planted on 15 April rather than 29 April (Table 27). For the earlier-planted crops, yields decreased from c. 24 to 18 t/ha as soil water content at cultivation increased from Moist to Over-wet but for crops planted on 29 April, yields were numerically smaller for the Moist cultivation regime plots. At the third harvest, scheduled irrigation increased tuber yield by c. 10 t/ha but yield was not affected by date of planting or soil moisture content at cultivation. As noted at the second harvest, yields of the crops planted on 15 April decreased from 44 to 35 t/ha as the soil at cultivation became wetter but for crops planted on 29 April, the Moist soil cultivation treatment had the smallest yield. At final harvest in late September, neither planting date nor soil moisture content at cultivation had any significant effect on tuber yield, however compared with Unirrigated crops, irrigation increased tuber yields by c. 10 t/ha . For crops planted on 15 April, yields were numerically larger when the soil had been cultivated Moist or at Field Capacity when compared with yields in soils cultivated when wetter but this difference was not statistically significant. For the later planting, numerical difference in yield between soil moisture contents at cultivation were smaller.

Date of planting	Irrigation regime	Soil cultivation regime	17 July	6 August	28 September
15 April	Unirrigated	Moist	20.5	39.5	54.9
		Field Capacity	20.3	35.5	56.8
		Wet	20.8	35.1	50.0
		Over-wet	15.7	31.3	49.3
	Irrigated	Moist	28.2	47.7	61.1
		Field Capacity	28.8	45.5	63.9
		Wet	21.4	35.7	59.4
		Over-wet	20.4	40.1	61.3
29 April	Unirrigated	Moist	12.9	29.4	53.0
		Field Capacity	18.0	34.3	51.6
		Wet	17.6	32.7	55.0
		Over-wet	17.4	33.1	59.8
	Irrigated	Moist	19.7	42.9	66.0
		Field Capacity	23.5	46.8	70.4
		Wet	23.1	45.8	64.4
		Over-wet	24.3	47.5	67.2
		S.E.	2.08	2.70	3.95
Means					
15 April			22.0	38.8	57.1
29 April			19.6	39.1	60.9
		S.E.	0.74	0.95	1.40
	Unirrigated		17.9	33.9	53.8
	Irrigated		23.7	44.0	64.2
		S.E.	0.74	0.95	1.40

TABLE 27. EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON TUBER FRESH WEIGHT YIELD > 10 MM (T/HA) IN EXPT 2009A. S.E. BASED ON 30 D.F.

Early planted crops had consistently higher tuber dry matter concentrations than late-planted crops (Table 28). Irrigation decreased dry matter concentration at the harvests on 17 July and 28 September, but following a wet period in mid-July, on 6 August Unirrigated crops had significantly lower dry matter concentrations than Irrigated crops. For the two harvests in July and August, the effect of cultivation regime on dry matter concentration differed between planting dates, as late-planted crops had higher dry matter concentrations when they were planted in soil cultivated at Field Capacity, Wet and Over-wet water contents, which was associated with late emergence of the late-planted Moist-cultivated crop due to the dry seedbed. There was little effect of cultivation regime on dry matter concentration for the early planting at any harvest and by final harvest, there was no overall effect of cultivation regime on dry matter concentration.

		19 or 23 June	17 July	6 August	28 September
Date of planting	15 April	13.8	17.8	20.0	25.6
	29 April	11.9	16.6	18.8	24.9
	S.E. (30 D.F.)	0.39	0.12	0.12	0.17
Soil cultivation regime	Moist	12.2	16.8	19.1	24.8
	Field Capacity	13.0	17.5	19.9	25.6
	Wet	13.2	17.2	19.5	25.6
	Over-wet	13.1	17.2	19.2	25.1
	S.E. (30 D.F.)	0.56	0.16	0.17	0.24
Irrigation regime	Unirrigated	12.7	18.0	18.4	26.5
	Irrigated	13.0	16.4	20.0	24.0
	S.E. (30 D.F.)	0.39	0.12	0.12	0.17

TABLE 28. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON TUBER DRY MATTER CONCENTRATION (%) IN EXPT 2009A

4.2.2.6. Total dry matter yield, radiation use efficiency and the onset of tuber bulking

Total dry matter (DM) yields at final harvest were not affected by planting date, irrigation or cultivation regimes (Table 29). The average radiation use efficiency (RUE) for total DM production was 1.31 t DM/TJ, similar to previous seasons. Radiation use efficiency was greater for crops that received irrigation than Unirrigated crops, similar to the experiment in 2008. Radiation use efficiency was greater for crops planted on 29 April than on 15 April. It is possible that this may be due to the later-planted crops growing in a duller radiation environment than the earlier-planted crops. However, the smaller RUE of the earlier plantings may also be due to poor recovery of senesced foliage leading to underestimates of total DM yield. The effects of water content at cultivation on RUE were not significant. On average each TJ of solar energy absorbed by the crop was associated with the production of c. 1.12 t tuber DM, lower than found in 2008 (1.30 t DM/TJ). The RUE for tuber DM production was increased by irrigation but was not significantly affected by any other treatment. The average interval between emergence and the apparent onset of tuber bulking was c. 28 days (Table 29) and assuming tuber initiation occurred at c. 18 DAE there was an interval of c. 10 days between initiation and bulking. Similar values for Maris Piper have been found in previous soil conditions experiments at CUF. The interval between emergence and tuber bulking was shorter for crops planted on 29 April than on 15 April and in the Unirrigated than the Irrigated crops but soil water content at cultivation had no significant effect on the start of bulking.

		Total DM yield on 28 September (t/ha)	RUE total DM (t/TJ)	RUE tuber DM (t/TJ)	Start of tuber bulking (DAE)
Date of planting	15 April	17.43	1.24	1.09	29.8
	29 April	18.67	1.37	1.15	25.3
	S.E. (30 D.F.)	0.461	0.020	0.025	0.63
Soil cultivation regime	Moist	18.03	1.31	1.10	27.4
	Field Capacity	18.47	1.28	1.14	28.2
	Wet	17.46	1.30	1.12	27.4
	Over-wet	18.26	1.32	1.12	27.2
	S.E. (30 D.F.)	0.652	0.028	0.035	0.89
Irrigation regime	Unirrigated	17.73	1.25	1.07	28.8
	Irrigated	18.38	1.36	1.17	26.3
	S.E. (30 D.F.)	0.461	0.020	0.025	0.63

TABLE 29. MAIN EFFECTS OF PLANTING DATE, SOIL CULTIVATION REGIME AND IRRIGATION ON TOTAL DM YIELD, RADIATION USE EFFICIENCY (RUE) AND THE APPARENT START OF TUBER BULKING (DAYS AFTER EMERGENCE, DAE) IN EXPT 2009A

4.2.2.7. Common scab and tuber cracking

There were no tubers without common scab. The incidence of tubers with < 5 % surface area infected with scab was much greater in Irrigated crops than in Unirrigated and soils cultivated Wet and Over-wet had more tubers with only slight levels of scab than Moist and Field Capacity, particularly where irrigated (Table 30). There was less severe scab for late-plantings (20.8 % surface area) than early (26.0 %) and for Irrigated compared with Unirrigated (Table 30). Cultivation regime had no effect on severity of scab in Unirrigated crops but was lower in Wet and Over-wet than Moist or Field Capacity cultivation regimes in Irrigated crops. Only 2 % of tubers had external cracking and there were no treatment effects.

	Incidence < 5 % SA (%)		**Incidence < 5 % SA ang.**		**Severity (% SA)**	
Cultivation regime	Unirrigated	Irrigated	Unirrigated	Irrigated	Unirrigated	Irrigated
Moist	14.5	29.3	19.3	32.0	30.0	21.7
Field Capacity	12.0	23.9	16.5	28.5	26.8	22.3
Wet	21.3	47.7	24.9	43.1	25.6	15.6
Over-wet	18.7	51.6	23.2	45.9	28.6	13.0
S.E. (30 D.F.)	-		2.78		2.33	

TABLE 30. COMMON SCAB INCIDENCE (PROPORTION OF TUBERS WITH < 5 % SURFACE AREA (SA) INFECTED) AND SEVERITY (% SURFACE AREA) IN EXPT 2009A

4.3. Experiment 2009b

4.3.1. Emergence and tuber initiation

There was a small difference in date of 50 % plant emergence between Maris Piper (21 May) and Vales Sovereign (23 May) but there was a protracted period of emergence over the experimental area so that initial emergence (13 May) to 95 % emergence took 20 days. Hermes was much later commencing emergence than the other two varieties, reaching 50 % emergence on 31 May, with initial emergence (22 May) to 95 % emergence taking 22 days. This protracted emergence had a consequential effect on tuber initiation. Maris Piper commenced initiation on 31 May, 18 days after initial emergence. The date of 50 % initiation was 4 June, 15 days after 50 % emergence. All sampled plants had initiated by 8 June. In Vales Sovereign, initiation commenced on 2 June (20 days after initial emergence), with 50 % of plants initiated on 6 June (14 days after 50 % emergence). All sampled plants had tubers by 10 June. Hermes commenced initiation on 9 June (18 days after initial emergence) and reached 50 % initiation on 13 June (13 days after 50 % emergence). On 17 June, all sampled plants had tuberized.

4.3.2. Ground cover

As Hermes emerged later than Maris Piper and Vales Sovereign, ground cover development was delayed. As early as 9 June, early over-watered plots (I+ 0-3) had more advanced ground cover development than I and I- plots. This difference was maintained until ground covers approached 100 % (Figure 34). However, I+ 0-3 plots did not attain complete cover in Hermes and Vales Sovereign (maximum 97-98 %) and senescence started in this treatment only 2-3 weeks after maximum cover. The canopies of early over-watered plots were almost fully senesced by final harvest in September and the decrease in ground cover was greatest in Hermes and Vales Sovereign. There was no significant difference in ground cover in Hermes and Vales Sovereign between any of the other irrigation treatments, even between irrigated and unirrigated plots. Generally, varieties had similar patterns of ground cover development and senescence when subject to water shortage or excess but I- Maris Piper senesced earlier than I, whereas in Hermes and Vales Sovereign this did not occur. Over-watering for 3 weeks after tuber initiation was extremely detrimental to canopy survival, whereas later over-watering (10-13 weeks after initiation) had no effect on ground cover compared with normal full irrigation.

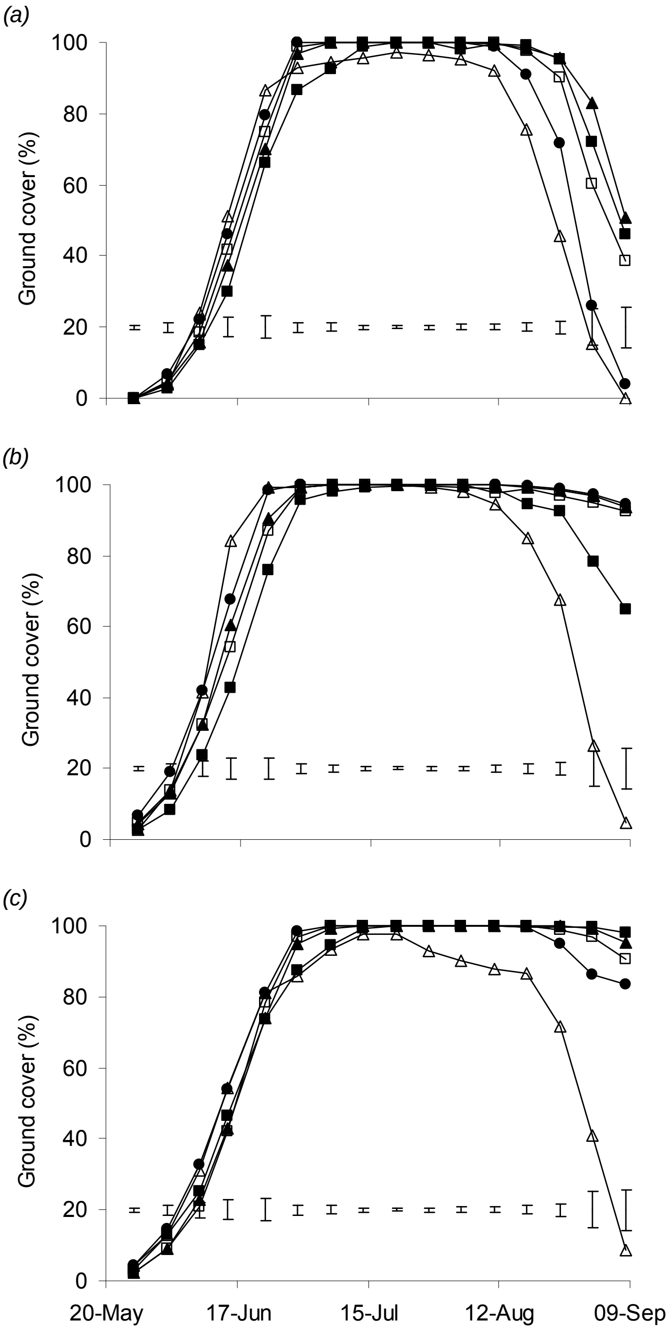

FIGURE 34. GROUND COVER IN (A) HERMES; (B) MARIS PIPER; (C) VALES SOVEREIGN IN EXPT 2009B. I-, ■; I, □; I- 4-6, ▲; I+ 0-3, △; I+ 10-13, ●. S.E. BASED ON 27 D.F.

4.3.3. Soil moisture deficits and water contents

4.3.3.1. Modelled soil moisture deficit

Reference crop evapotranspiration demand in June and July (3.54 mm/day) was higher than average for these months in Cambridge (3.17 mm/day) but August was average (3.13 mm/day). Soil moisture deficits in unirrigated crops increased to 50-54 mm in mid-July, then there was almost adequate rainfall for the next 4 weeks to satisfy demand before a dry late August and September caused unirrigated crops to exist on soil reserves, so that by final harvest deficits had reached c. 56-60 mm (Figure 35). Deficits in irrigated crops averaged 11 mm with a maximum of 25 mm. During the restricted period of I- 4-6 treatments, deficits reached c. 45 mm. Deficits during over-watered periods in I+ 0-3 and I+ 10-13 treatments were modelled as zero since the model calculated that excess water would drain away prior to the next irrigation and that the soil water status would not affect root function. Clearly, this was not the case (see next section).

4.3.3.2. Measured soil water content

Measurements of soil water content with Theta probes were unreplicated, therefore the values for different treatments should be treated with caution. The soil water contents are based on the top 20 cm of soil only as this was the depth where the probe sensors were located. The probe data indicated that the over-watered treatments were maintained above Field Capacity (0.32 m3/m3) for the entire duration of the period, averaging 0.37 m3/m3 for I+ 0-3 treatments and 0.36 m3/m3 for I+ 10-13 treatments (Figure 36). Total pore space of the same soil type in an adjacent experiment was typically 60 % at 15-20 cm depth, therefore the air-filled pore space (c. 24 %) of these over-filled soils should still have been sufficient for root respiration but this assumes no “plugging” of pores with degraded silt and clay particles. The minimum soil water content in the ridge in irrigated (I) treatments during the scab control period was c. 0.26 m3/m3, which would be expected to result in reasonably good scab control. The minimum soil water content in I- treatments averaged 0.22 m3/m3 in early September.

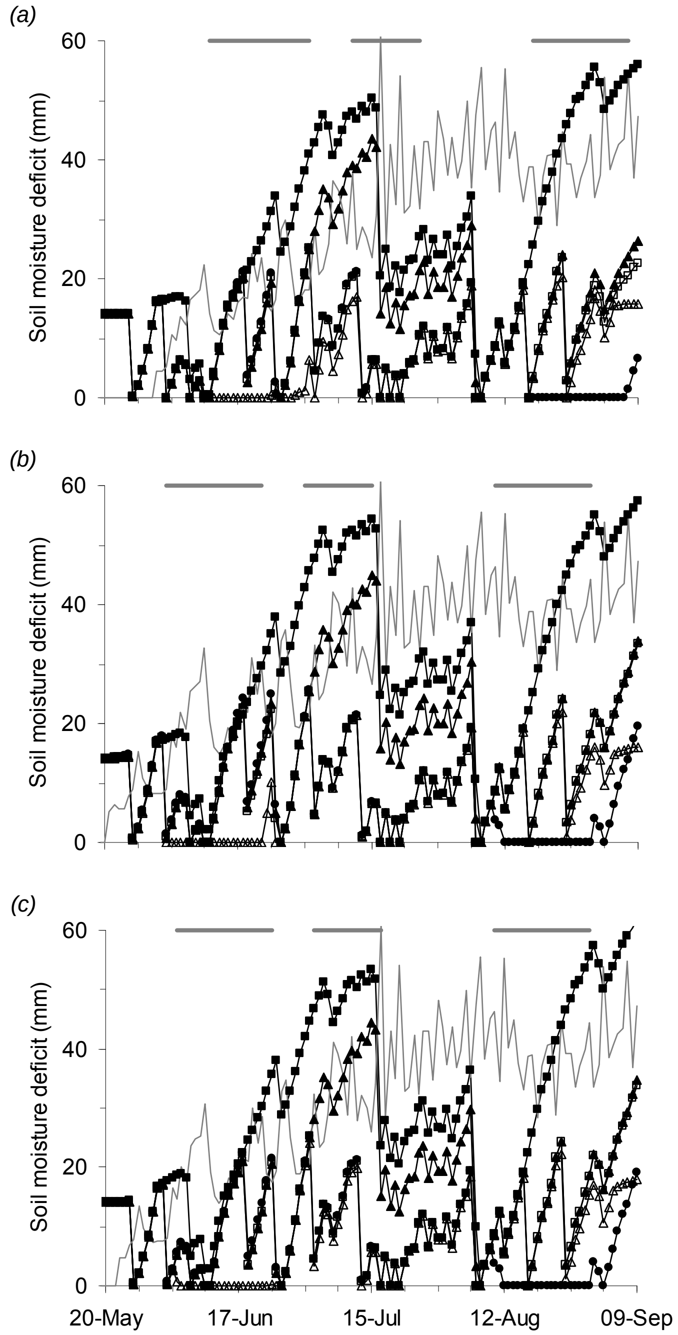

FIGURE 35. MODELLED SOIL MOISTURE DEFICITS IN EXPT 2009B. (A) HERMES; (B) MARIS PIPER; (C) VALES SOVEREIGN. I-, ■; I, □; I-4-6, ▲; I+ 0-3, △; I+ 10-13, ●. THICK SOLID LINES INDICATE PERIODS OF IRRIGATION RESTRICTION/OVER-WATERING IN I+ 0-3 , I- 4-6 AND I+ 10-13, RESPECTIVELY.

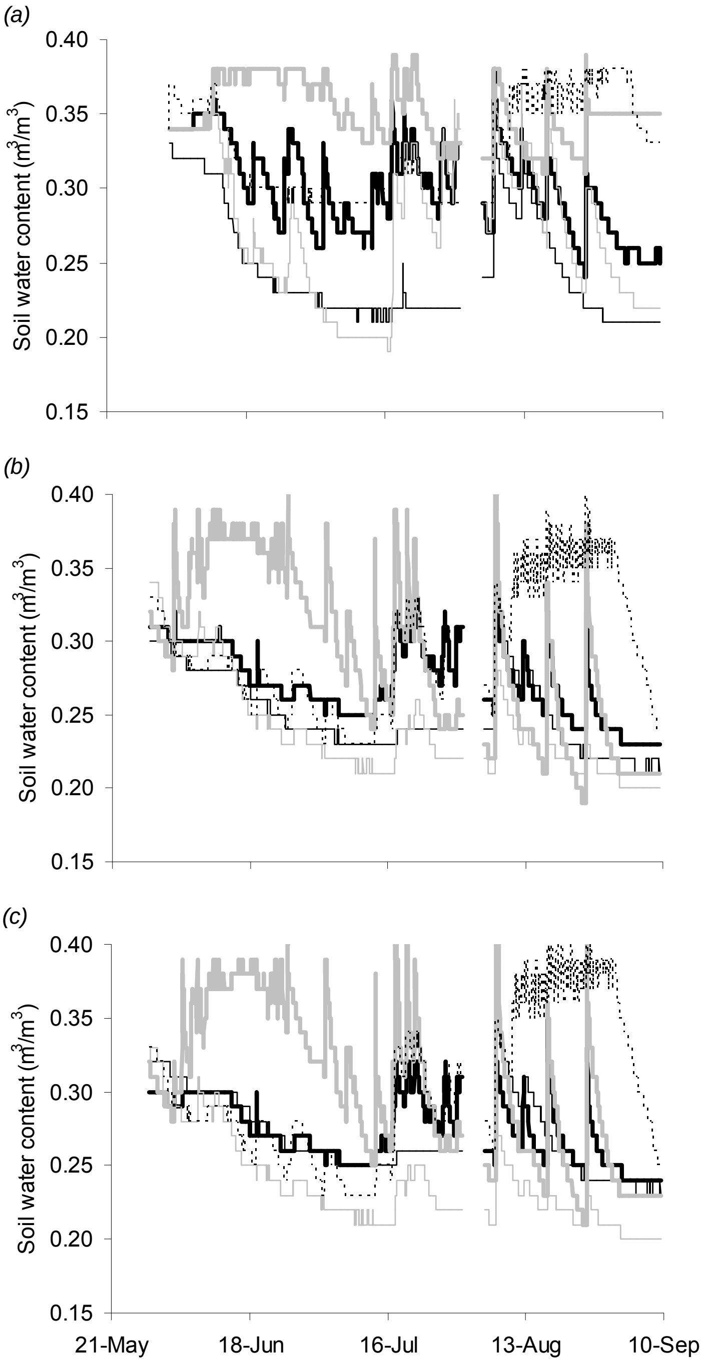

FIGURE 36. MEASURED SOIL WATER CONTENT IN TOP 20 CM OF RIDGE IN EXPT 2009B. (A) HERMES; (B) MARIS PIPER; (C) VALES SOVEREIGN. I-, —; I, ▬; I- 4-6, —; I+ 0-3, ▬; I+ 10-13, ---.

4.3.4. Stomatal resistance

Examining differences in stomatal resistance between varieties over a time course was slightly confounded by the delayed emergence in Hermes compared with Maris Piper and Vales Sovereign. Nevertheless, for a large part of the measurement period during June and July, Vales Sovereign had significantly higher stomatal resistance at 15:00 h than either Hermes or Maris Piper although there were slight differences in how varieties responded to different irrigation treatments (Figure 37). However, the differences in resistance between varieties were not consistently large enough to point to real differences in stomatal function that may have affected water use efficiency. On three occasions, stomatal resistance was measured at 09:00, 12:00 and 15:00 h to examine the diurnal change in stomatal function. The days were selected on the basis of predicted hot and sunny weather and for the two days in late June, the daily reference crop evapotranspiration was between 4.6 and 5.3 mm, which for Cambridge is a high potential water use. On 23 June, canopies were c. 70-80 % ground cover for all varieties. Unirrigated crops started the day with higher stomatal resistance than other crops and resistance increased significantly faster between 09:00 and 12:00 h than in irrigated treatments (Figure 38). Thereafter, the difference between unirrigated and all other irrigated plots except I+ 0-3 remained constant. During the course of the day, stomatal resistance in I+ 0-3 plots remained low.

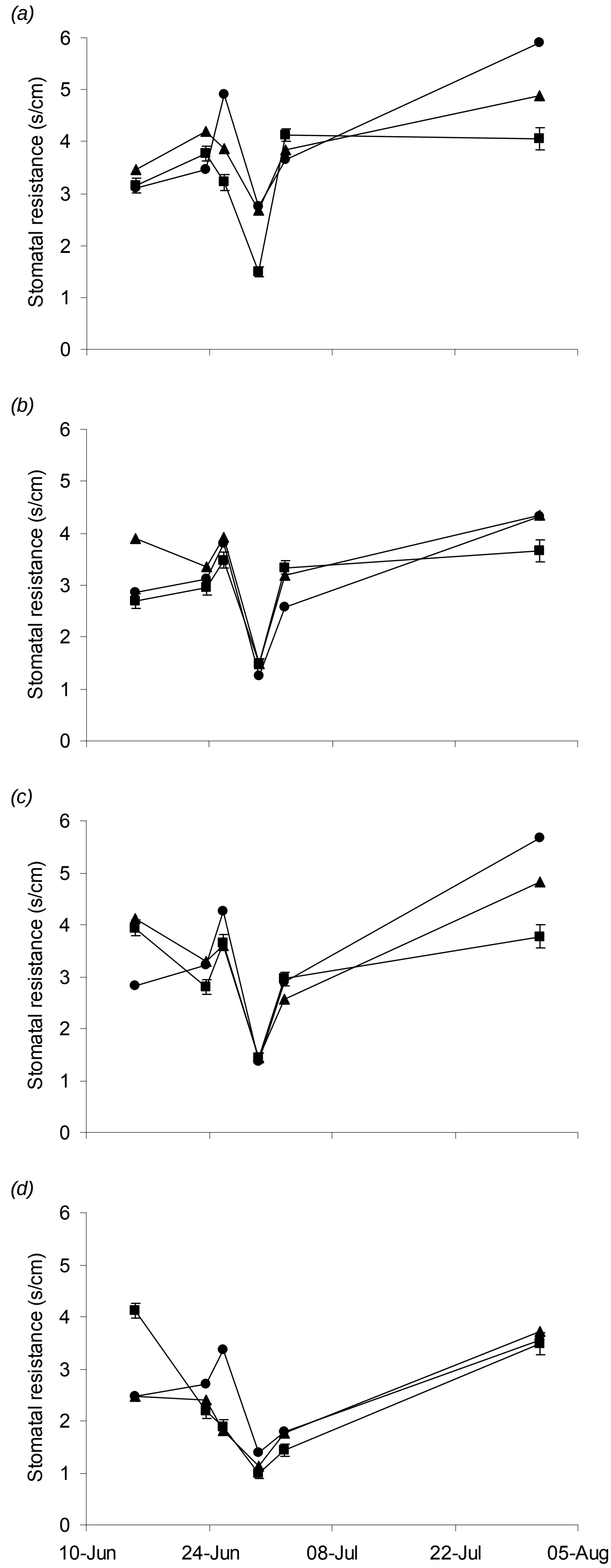

FIGURE 37. STOMATAL RESISTANCE (A) I-; (B) I; (C) I- 4-6; (D) I+ 0-3 IN EXPT 2009B. HERMES ■; MARIS PIPER, ▲; VALES SOVEREIGN ●. S.E. BASED ON 16 D.F. (DATA NOT TAKEN FOR I+ 10-13 ON ALL OCCASIONS AND THEREFORE NOT SHOWN).

By 29 June, canopies were almost complete but it was still c. 4 weeks prior to crops reaching maximum rooting density. A slightly different pattern in change in stomatal resistance to 23 June was observed. Stomatal resistance in unirrigated Maris Piper and Vales Sovereign continued to increase throughout the day whereas there was virtually no change in resistance in all other irrigation regimes (Figure 39). In Hermes, by contrast, the resistance in unirrigated crops only increased very slightly during the day and at a rate similar to I treatments.

Evaporative demand was lower on 31 July (3.4 mm) than on the two measurement days in June. The stomatal resistance of all treatments increased throughout the day. In Hermes and Maris Piper, the differences in resistance that were apparent between irrigation regimes at 09:00 h were maintained throughout the day whereas in Vales Sovereign the differences increased during the day (Figure 40). Again, despite the over-irrigation period ending 4-5 weeks earlier, I+ 0-3 treatments had the lowest stomatal resistance. Unirrigated plots had the highest resistance and crops that had just completed a 2-week water restriction (I- 4-6) had higher stomatal resistance in Maris Piper and Vales Sovereign than normally-irrigated (I) plots.

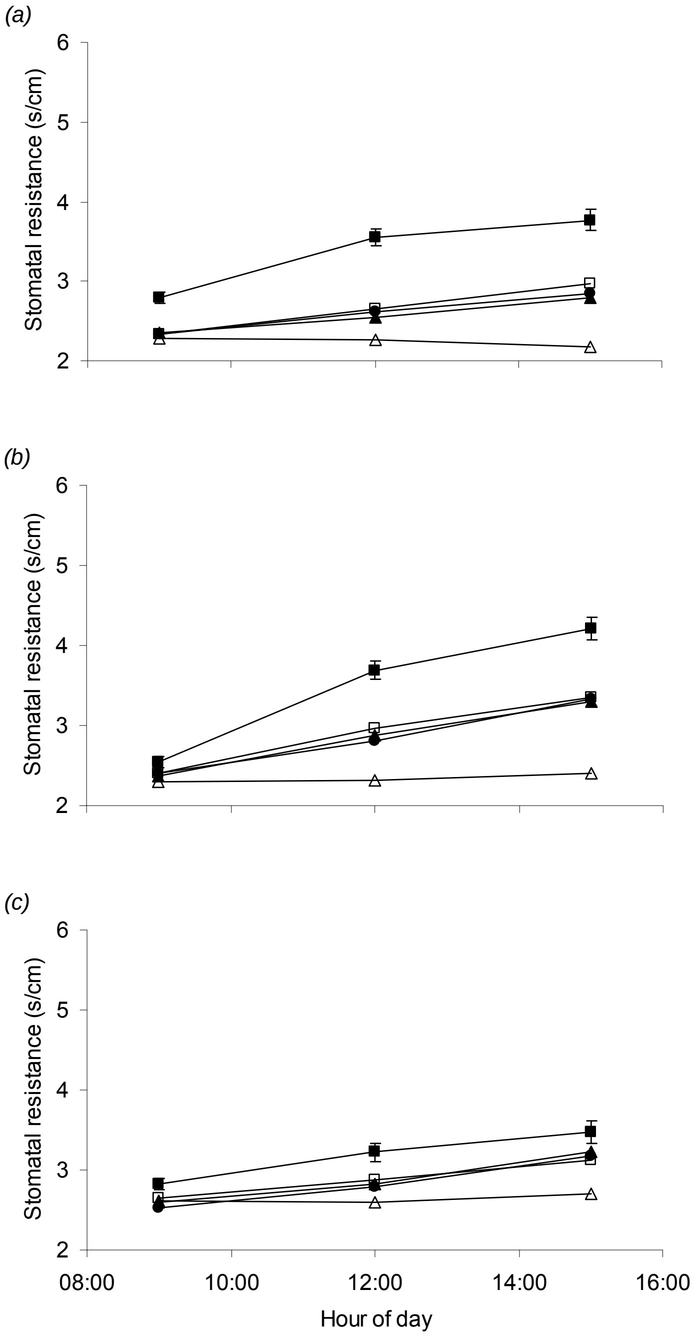

FIGURE 38. STOMATAL RESISTANCE ON 23 JUNE (A) HERMES; (B) MARIS PIPER; (C) VALES SOVEREIGN IN EXPT 2009B. I-, ■; I, □; I- 4-6, ▲; I+ 0-3, △; I+ 10-13, ●. S.E. BASED ON 27 D.F.

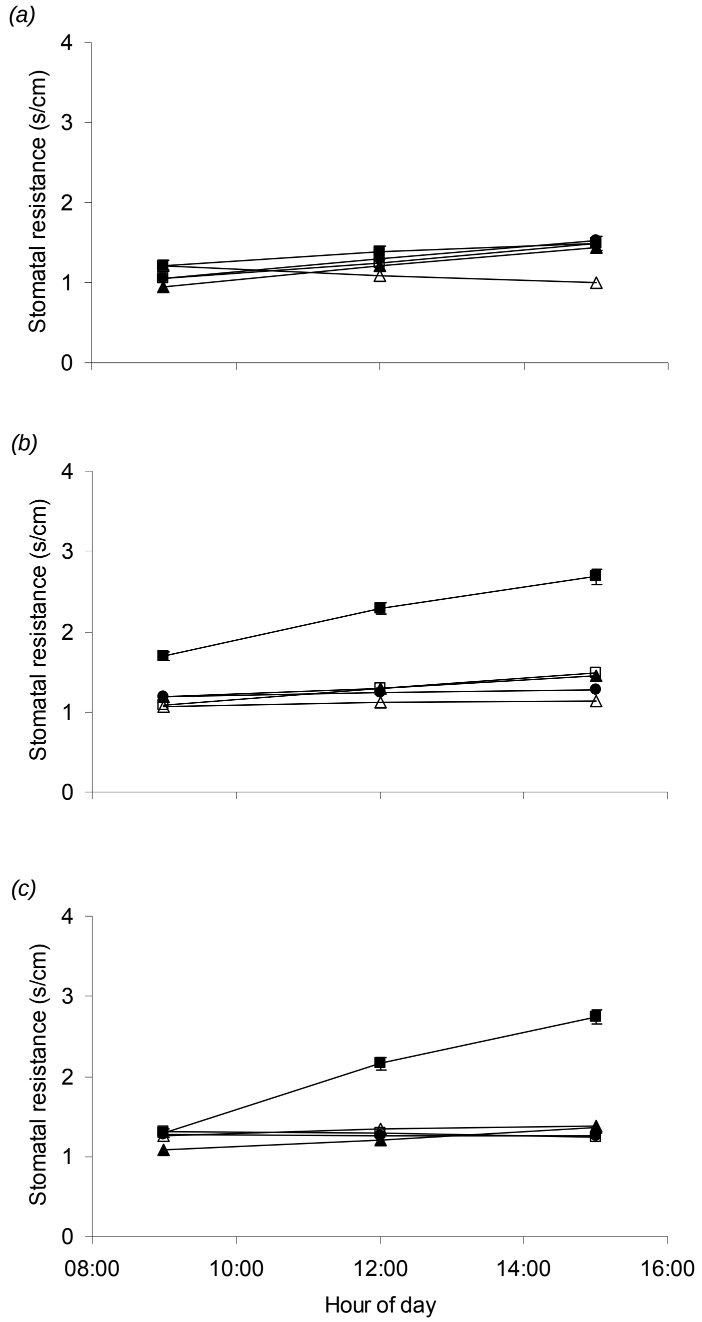

FIGURE 39. STOMATAL RESISTANCE ON 29 JUNE (A) HERMES; (B) MARIS PIPER; (C) VALES SOVEREIGN IN EXPT 2009B. I-, ■; I, □; I- 4-6, ▲; I+ 0-3, △; I+ 10-13, ●. S.E. BASED ON 27 D.F.

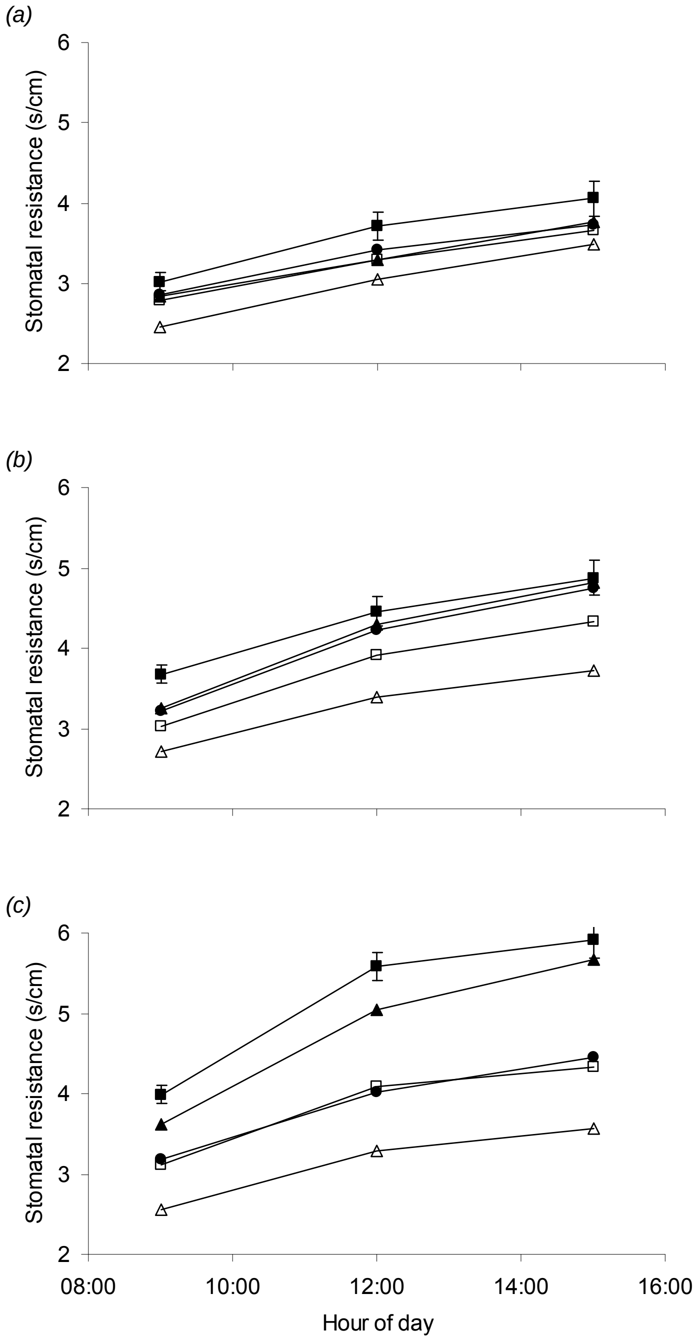

FIGURE 40. STOMATAL RESISTANCE ON 31 JULY (A) HERMES; (B) MARIS PIPER; (C) VALES SOVEREIGN IN EXPT 2009B. I-, ■; I, □; I- 4-6, ▲; I+ 0-3, △; I+ 10-13, ●. S.E. BASED ON 27 D.F.

4.3.5. Number of tubers and tuber yield

There was a very large increase in the number of tubers in early over-irrigated plots of all varieties compared to all other irrigation regimes that was not caused by variation in the number of stems (Table 31). All plots except unirrigated were irrigated for the first time at tuber initiation and canopies were similar across irrigation regimes at this stage. Canopy development was faster in early over-irrigated plots over the next 2 weeks which resulted in a greater light absorption, but this is unlikely to explain the magnitude of the effect. The ground cover in the 2 weeks post initiation in Hermes and Vales Sovereign was increased in I+ 0-3 treatments in relative terms by 17 % compared with the mean of all other irrigated treatments, whereas in Maris Piper, there was a 30 % increase. However, the number of tubers in I+ 0-3 plots was 33-40 % greater than I and I+ 10-13 plots. It is uncertain whether the low soil moisture deficits in I+ 0-3 plots aided retention of initiated tubers in the 2-3 weeks post initiation or stimulated an increased number of tubers to be initiated but there were many more tubers in the 20-50 mm grade in I+ 0-3 plots than other treatments. Consequently, mean tuber size (μ) was much smaller for I+ 0-3 plots than other irrigation regimes (Table 31) but the coefficient of variation of tuber size (σ, data not shown) was not affected by any treatment, suggesting that there was not a skewed distribution of tuber sizes in I+ 0-3 plots compared with other irrigation treatments. The size of these increases in number of tubers in early over-watered plots compared with normal irrigation has not been seen in previous experiments conducted at CUF.

The highest fresh and dry weight yields were obtained with the “normal” irrigation (I) practice (Table 31). Restricting irrigation to any extent reduced yields significantly. Over-watering in August had little detrimental effect on yield but early over-watering reduced yields considerably, such that the yields were similar to completely unirrigated crops. Clearly, irrigating excessively to avoid common scab control can have serious consequences. Effects of irrigation regime on yield were similar for all three varieties, indicating no difference in irrigation response or drought tolerance.

Variety	Irrigation regime	No. of mainstems (000/ha)	No. of tubers (000/ha)	Total yield (t/ha)	Yield > 40 mm (t/ha)	Tuber dry matter yield (t/ha)	Mean tuber size, μ (mm)
Hermes	I-	102	405	48.1	46.3	11.1	59.4
	I	133	461	63.2	60.9	14.6	59.6
	I- 4-6	102	426	58.4	56.1	12.9	60.6
	I+ 0-3	101	580	44.7	38.9	10.2	49.8
	I+ 10-13	101	413	59.3	57.4	14.0	60.5
Maris Piper	I-	130	470	52.6	49.4	12.5	57.4
	I	147	523	66.2	63.0	15.4	58.0
	I- 4-6	112	401	57.8	55.6	13.3	60.7
	I+ 0-3	144	712	56.7	47.5	11.5	48.6
	I+ 10-13	140	491	66.8	64.4	15.1	58.5
Vales Sovereign	I-	163	360	60.5	58.3	12.1	62.6
	I	147	414	72.4	69.3	14.5	62.0
	I- 4-6	137	351	66.5	64.7	13.7	63.3
	I+ 0-3	176	538	58.5	52.7	11.7	53.3
	I+ 10-13	171	373	70.4	69.1	14.2	63.1
S.E. (27 D.F.)		13.8	43.1	4.07	4.09	0.81	1.34

TABLE 31. NUMBER OF MAINSTEMS AND TUBERS AND TUBER YIELDS AT FINAL HARVEST IN EXPT 2009B

4.3.6. Tuber dry matter concentration

Vales Sovereign had a lower tuber dry matter concentration than Hermes or Maris Piper. Irrigation regime had a large effect on dry matter concentration but effects were not entirely as expected. Initially, unirrigated crops had higher dry matter concentration than irrigated, with early over-irrigated crops having significantly lower dry matter concentrations than other irrigated treatments (Figure 41). However, by c. 3-4 weeks after tuber initiation, the tuber dry matter concentrations in crops which had been over-watered during tuber initiation had increased to similar values to those which had received less frequent irrigation (I, I- 4-6, I+ 10-13). Over the next 4 weeks, the dry matter concentration of I+ 0-3 crops increased more rapidly than other crops and this difference was largely maintained through to September when there was a 1.5 % higher dry matter concentration in I+ 0-3 crops than the rest. The maximum difference in dry matter concentration between early over-watered crops and the rest was 3.4 % in early August. The likely effect of early-over watering on dry matter concentration was probably the root death caused by anaerobic conditions in the soil maintained above Field Capacity for 3 weeks following tuber initiation. This would have reduced the uptake potential of water when frequent irrigation was ceased.

The restricted water regime between 4 and 6 weeks after tuber initiation caused tuber dry matter concentration to increase by c. 1.7 % in Hermes during the two weeks compared with irrigated crops which received 48 mm of irrigation over the period but the change, albeit in the same direction, was not significant in Maris Piper and Vales Sovereign. However, rain fell at the end of the restricted period, so that one week later the dry matter concentrations in the restricted I- 4-6 treatment were not significantly different from the fully-irrigated I treatments and this remained so until final harvest. This contrasts with some previous work where water restrictions around 4-6 weeks after initiation have led to significant permanent increases in dry matter concentration (c. 2-3 %) compared with unrestricted irrigation. Late over-watering (I+ 10-13) had little or no effect on dry matter concentration. Despite considerable differences in water supply during the course of the season, the only significant effect in dry matter concentration that remained at final harvest was that caused by the early over-watering regime.

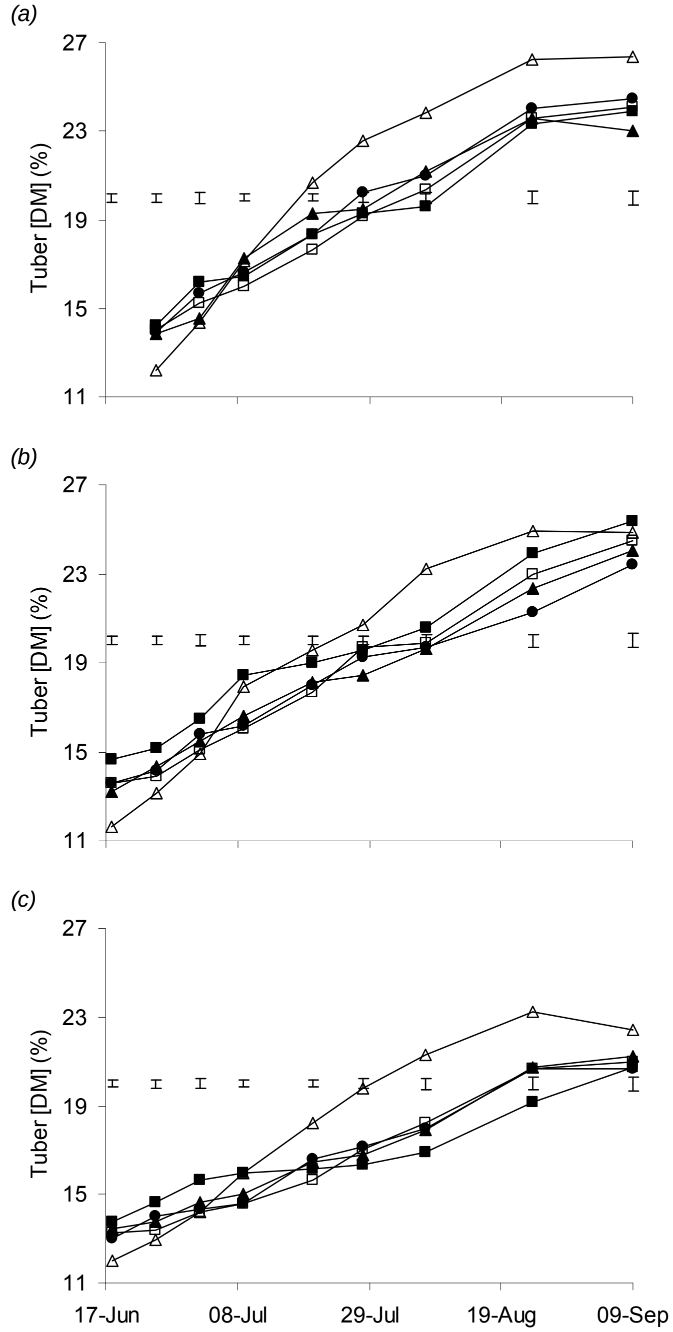

FIGURE 41. TUBER DRY MATTER CONCENTRATION ([DM]) IN *(A)* HERMES; *(B)* MARIS PIPER; *(C)* VALES SOVEREIGN IN EXPT 2009B. I-, ■; I, □; I- 4-6, ▲; I+ 0-3, △; I+ 10-13, ●. S.E. BASED ON 27 D.F.

4.3.7. Tuber cracking

It is widely believed that cracking occurs as a consequence of relief of water stress after a drought period and the experiment was designed to include both periods of drought as well as early and late over-supply of water in order to test the various hypotheses behind cracking. Greenvale AP were interested in testing their new variety Vales Sovereign alongside established varieties, particularly in relation to tuber cracking and optimum common scab control.

In all irrigation treatments, some tubers had external growth cracks. Vales Sovereign had the greatest incidence of cracking but the cracks were mostly of a different form to those observed on Hermes and Maris Piper tubers (Figure 42). Cracking in Maris Piper was almost universally single, deep (3-8 mm) cracks traversing along the longitudinal axis, whereas in Hermes the cracks were mostly deep, multiple (3-4) cracks emanating from the apical end. In Vales Sovereign, the cracks were mostly superficial (1-3 mm in depth), emanating from a focus centred on a lenticel and usually with 2-4 cracks arising from the same point. These cracks were shallow but were multi-armed and covered a large surface area where there was high incidence of cracking on an individual tuber.

(a)

(b)

(c)

FIGURE 42. TYPICAL CRACKING SYMPTOMS IN (A) HERMES; (B) MARIS PIPER; (C) VALES SOVEREIGN IN EXPT 2009B.

Vales Sovereign had a much higher incidence of cracking than Hermes or Maris Piper since many tubers had some superficial cracking (Table 32). In Hermes and Maris Piper, over-irrigating for 3 weeks after initiation increased the incidence of both deep and superficial cracks compared with all other irrigation treatments. In Vales Sovereign, however, fully-irrigated crops had a greater incidence of cracking than those with a restriction in irrigation (I-, I- 4-6), mainly as a consequence of changes in superficial cracking. Early over-watering did not alter the proportion of tubers with superficial cracking compared with normally-irrigated (I) crops, however late-season over-watering (I+ 10-12) increased the incidence of superficial cracking significantly compared with early over-watering, I+ 0-3. Early over-watering increased the incidence of tubers suffering from deep cracks, whereas superficial cracking in Vales Sovereign was increased by late over-watering.

		Total cracks			**Deep cracks**		**Superficial cracks**	
Variety	**Irrigation regime**	**Incidence (%)**	**Ang. trans.†**	**% SA affected**	**Incidence (%)**	**Ang. trans.**	**Incidence (%)**	**Ang. trans.**
Hermes	I-	9.3	17.7	6.5	4.7	12.1	4.6	12.3
	I	10.7	17.9	7.2	4.3	10.9	6.4	13.9
	I- 4-6	8.9	17.0	8.2	3.9	10.8	5.0	11.9
	I+ 0-3	27.4	31.5	24.5	11.2	19.3	16.3	23.7
	I+ 10-13	9.1	15.0	7.0	3.2	6.0	5.9	12.6
Maris Piper	I-	5.6	13.3	4.2	1.6	5.6	4.0	11.4
	I	5.1	12.4	4.2	0.3	1.8	4.8	12.0
	I- 4-6	12.5	17.9	8.9	6.9	10.9	5.6	12.7
	I+ 0-3	22.9	28.7	15.9	12.0	20.2	10.9	19.3
	I+ 10-13	6.9	15.2	5.6	2.0	4.7	4.9	12.6
Vales Sovereign	I-	26.1	30.3	12.9	1.0	3.3	25.2	29.7
	I	55.0	47.9	28.9	1.0	4.6	54.0	47.3
	I- 4-6	30.4	33.3	14.6	1.8	7.5	28.7	32.2
	I+ 0-3	54.9	47.8	26.7	2.8	9.1	52.1	46.2
	I+ 10-13	77.4	61.7	42.1	0.8	3.0	76.6	61.1
S.E. (27 D.F.)			3.39	3.19		3.54		2.52

†Angularly transformed data for statistical analysis

TABLE 32. TUBER CRACKING INCIDENCE AND SEVERITY IN EXPT 2009B

The hypothesis examined was that cracking might be caused by internal hydration pressure that exceeded the retaining strength of the periderm, thereby causing a failure along one or more planes of weakness. The water potential of tubers in early over-irrigated plots was very low in both over-watered periods but was slightly lower (i.e. tubers were more hydrated) during the early over-watering period than the late (Table 33). Irrigated and unirrigated plots showed slight differences in water potential depending on when they were sampled within each respective period but there were fluctuations in soil moisture deficits during the three week periods that would probably have altered tuber water potential slightly. There was no significant difference in water potential between varieties, indicating that hydration status alone was not a major cause of differences in tuber cracking between varieties.

Variety	Irrigation regime	15 June	22 June	17 August	25 August
Hermes	I-	1.02	1.84	1.28	2.15
	I	0.99	1.19	1.16	1.58
	I+ 0-3	0.32	0.32	-	-
	I+ 10-13	-	-	0.45	0.41
Maris Piper	I-	1.08	1.95	1.40	2.15
	I	1.12	1.34	1.09	1.73
	I+ 0-3	0.28	0.27	-	-
	I+ 10-13	-	-	0.39	0.36
Vales Sovereign	I-	0.98	1.76	1.20	2.02
	I	1.01	1.21	1.00	1.52
	I+ 0-3	0.26	0.28	-	-
	I+ 10-13	-	-	0.36	0.34
S.E. (16 D.F.)		0.104	0.177	0.121	0.199

TABLE 33. TUBER WATER POTENTIAL (BARS) ON TWO DATES IN EACH OVER-IRRIGATION PERIOD (I- 4-6 TREATMENT NOT MEASURED) IN EXPT 2009B

4.3.8. Common scab

All tubers were infected with common scab but the incidence of tubers with < 5 % surface area infected was lowest in Maris Piper (43.3 %) and similar in Hermes (73 %) and Vales Sovereign (81 %). In Maris Piper and Vales Sovereign, I+ 0-3 plots had more tubers with slight infection (< 5 % surface area) than other irrigated treatments, with the largest difference in Maris Piper (Table 34), which supports previous work at CUF. In Vales Sovereign, however, crops which received no irrigation during the 4 weeks after tuber initiation had the greatest proportion of tubers with only slight infection (< 5 % surface area). All plots of Maris Piper and Vales Sovereign received 15 mm of rain at the onset of tuber initiation which may have reduced scab infection in the I- treatment but the effect in Vales Sovereign may be an anomaly as it is difficult to explain in relation to previous work at CUF. The mean surface area infected with scab showed the same trends as for incidence, with unirrigated Maris Piper having the most severe scab and more frequent irrigation reducing the severity. In Vales Sovereign, tubers were much less severely affected by scab than in Maris Piper, but there was still significantly less severe scab where the soil was kept at, or above, Field Capacity during the susceptible phase rather than allowing the soil moisture deficit to increase to c. 20 mm before irrigating. It is important to note that soil moisture deficits in I, I- 4-6 and I+ 10-13 treatments were only c. 6 mm at initiation as these plots were irrigated with 21 mm on 2 June. There was no effect of irrigation regime on scab severity in Hermes.

Variety	Irrigation regime	Incidence < 5 % surface area %	Ang. trans.	Severity % SA affected
Hermes	I-	76.0	60.9	6.9
	I	72.0	58.5	6.4
	I- 4-6	70.7	57.7	6.4
	I+ 0-3	62.0	53.1	8.4
	I+ 10-13	83.3	67.9	5.0
Maris Piper	I-	39.3	36.0	20.9
	I	34.0	35.6	13.9
	I- 4-6	30.7	33.0	13.6
	I+ 0-3	68.0	55.8	6.8
	I+ 10-13	44.7	41.2	10.3
Vales Sovereign	I-	98.7	86.2	2.4
	I	71.3	57.7	6.7
	I- 4-6	76.5	61.6	5.7
	I+ 0-3	88.9	74.0	3.9
	I+ 10-13	68.3	55.8	6.7
S.E. (27 D.F.)			5.21	2.14

TABLE 34. COMMON SCAB INCIDENCE AND SEVERITY IN EXPT 2009B

4.4. Experiment 2009c

4.4.1. Planting depth and emergence

Planting was deeper in Bed (17.4 cm) profiles than Ridge (14.4 ± 0.34 cm) despite the automatic depth control on the planter. Soil was removed from the centre of the bed by the middle share on the planter in Ridge format which should have resulted in a greater depth of soil coverage. Apparently, the depth control was not sensing this change in finished ridge height. Increasing the pressure on the covering hood resulted in shallower planting (15.4 cm) than Minimum pressure (16.4 ± 0.34 cm). Destoning depth had no effect on planting depth.

The time taken from planting to 50 % plant emergence took on average 27 days and was delayed by c. 1 day by destoning deeply, planting in beds or increasing the pressure on the covering hoods to Maximum. The largest difference in emergence of 3 days was between Shallow destoning, Ridge profile and Minimum pressure with Deep destoning, Bed profile and Minimum pressure (Table 35). No ground cover measurements were taken during the season to check whether these small differences in emergence gave a significant advantage in early canopy development.

Profile	Bed		Ridge	
Hood pressure	Minimum	Maximum	Minimum	Maximum
Shallow destoning	27.5	28.1	26.0	26.8
Deep destoning	27.9	28.7	27.0	27.4
S.E. (14 D.F.)	0.32			

TABLE 35. DAYS FROM PLANTING TO 50 % PLANT EMERGENCE IN EXPT 2009C

4.4.2. Soil properties

4.4.2.1. Bulk density

The soil bulk density of the upper bed/ridge profile was initially measured just prior to emergence. When measured soon after planting, increasing the hood covering pressure increased soil bulk density (Table 36). Interestingly, at this time, the gravimetric moisture content of the Ridge profiles was lower (6.4 %) than Bed (7.3 ± 0.18 %), particularly where destoning was deep. When measured at the end of the season, bulk density had increased slightly from a mean value of 1.22 to 1.27 g/cm3, most probably as a consequence of natural consolidation, and Bed profiles had a significantly higher bulk density than Ridge (Table 36). There was an increase in density during the season but all treatments generally increased by similar amounts, except Ridge profiles created with Maximum pressure which did not alter.

Profile	**Bed**		**Ridge**	
Hood pressure	**Minimum**	**Maximum**	**Minimum**	**Maximum**
(a)				
Shallow destoning	1.22	1.27	1.15	1.26
Deep destoning	1.18	1.23	1.21	1.24
S.E. (14 D.F.)	0.031			
(b)				
Shallow destoning	1.35	1.31	1.26	1.23
Deep destoning	1.27	1.31	1.22	1.24
S.E. (14 D.F.)	0.040			

TABLE 36. SOIL DRY BULK DENSITY (G/CM3) ON (A) 22 MAY AND (B) 1 OCTOBER IN EXPT 2009C

4.4.2.2. Resistance

Shallow destoning reduced the depth of soil worked to c. 25 cm (30 cm below top of ridge/bed), consequently soil resistance was greater between 30-40 cm in Shallow-destoned plots than Deep (Figure 43). Resistances were low in the upper 40 cm, however, and unlikely to impede root growth significantly (Stalham et al. 2007). Soil resistance between 10 and 15 cm depth was increased by using Maximum pressure on the covering hoods rather than Minimum but only in Bed profiles not Ridge.

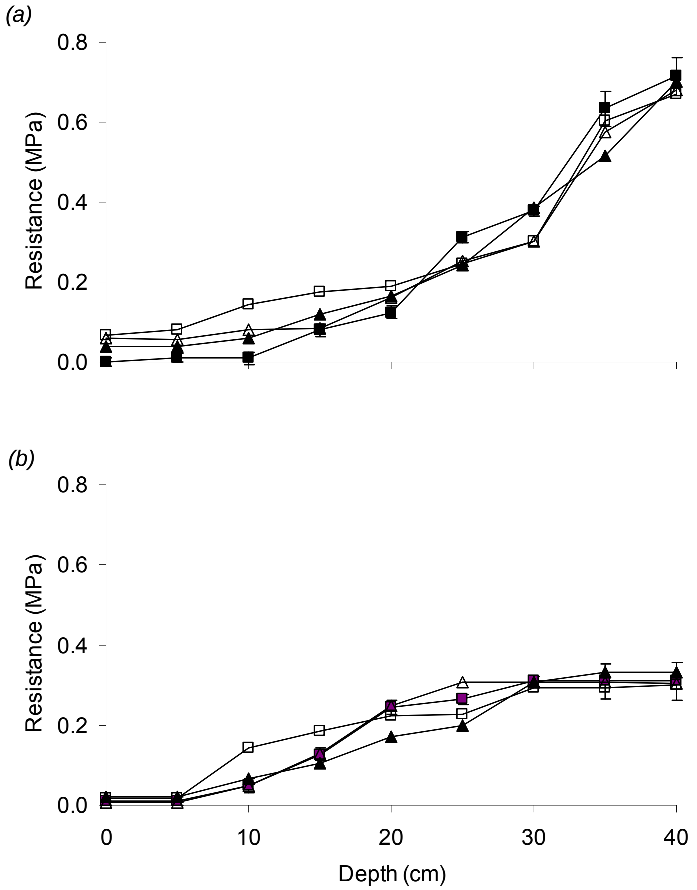

FIGURE 43. SOIL RESISTANCE MEASURED ON 22 MAY IN EXPT 2009C. *(A)* SHALLOW DESTONING; *(B)* DEEP DESTONING. BED MINIMUM PRESSURE, ■; BED MAXIMUM PRESSURE, □; RIDGE MINIMUM PRESSURE, ▲; RIDGE MAXIMUM PRESSURE, △.

4.4.2.3. Water infiltration

There were clear spatial differences in soil water content across beds following irrigation events. At the earlier sampling (12 June), plants were just about to commence tuberization and ground cover was low (c. 30 %) whilst at the later sampling (14 July) there was full canopy cover on all plots and this would have altered the shedding pattern of water from leaves. On 12 June, the soil was dry (10 % volumetric) in the upper 15 cm prior to irrigation. Before irrigation, the water content was greater within rows in Bed profiles than in Ridge, whereas Ridge furrows were wetter than the inter-row area in Bed profiles (Table 37). The difference between the row centre and furrow positions was greater in Ridges than Bed profiles. Following irrigation, Bed profiles were wetter in row centres than Ridge and the converse was true in the inter-row positions (Table 37). The difference in soil water content between row centre and inter-row positions was increased between Bed and Ridge profiles following irrigation, since more water was shed from the flanks of Ridge profiles into the furrows than in Bed profiles leaving the ridge center drier than in Bed profiles (Table 37).

Position Row centre	Profile Hood pressure	Bed Minimum	 Maximum	Ridge Minimum	 Maximum	S.E. (14 D.F.)
Pre-irrigation	Shallow destoning	9.3	9.9	8.4	8.8	0.33
	Deep destoning	9.5	9.9	8.8	8.9	
Post-irrigation	Shallow destoning	16.6	18.0	14.9	14.8	0.57
	Deep destoning	17.9	17.7	13.7	14.8	
Diff. post-pre	Shallow destoning	7.3	8.1	6.5	6.1	0.48
	Deep destoning	8.5	7.8	4.9	6.0	
Furrow						
Pre-irrigation	Shallow destoning	9.9	10.5	10.2	10.6	0.30
	Deep destoning	10.0	10.4	11.2	11.0	
Post-irrigation	Shallow destoning	17.7	17.6	20.0	19.6	0.39
	Deep destoning	18.0	17.4	20.0	19.6	
Diff. post-pre	Shallow destoning	7.8	7.1	9.7	9.0	0.54
	Deep destoning	8.0	7.0	8.8	8.6	
Diff. furrow-row						
Pre-irrigation	Shallow destoning	0.5	0.6	1.9	1.9	0.23
	Deep destoning	0.5	0.5	2.5	2.1	
Post-irrigation	Shallow destoning	1.1	-0.4	5.1	4.7	0.48
	Deep destoning	0.1	-0.4	6.3	4.7	
Diff. post-pre	Shallow destoning	0.6	-1.0	3.2	2.8	0.54
	Deep destoning	-0.4	-0.9	3.9	2.5	

TABLE 37. MEASUREMENTS AND CHANGES IN SOIL WATER CONTENT (% VOLUMETRIC) FOLLOWING IRRIGATION OF 18 MM ON 12 JUNE IN EXPT 2009C

On 14 July, the soil in the upper 15 cm (mean 14 % volumetric) prior to irrigation was wetter than on 12 June. Before irrigation, the water content was again greater within rows in Bed profiles than in Ridge, whereas Ridge furrows were wetter than the inter-row area in Bed profiles. The difference between the row centre and furrow positions was greater in Ridges than Bed profiles, however the difference between row centre and furrow locations was greater between Ridge and Bed profiles than on 12 June (Table 37 and Table 38). After the irrigation event (25 mm), Bed profiles were wetter in row centres than in Ridge and the converse was true in the inter-row positions (Table 37). The soil was much wetter post-irrigation (mean 23 % volumetric) than on 12 June (17 %) where the soil was drier to start with and a smaller amount (18 mm) was applied. The difference in soil water content between row centre and inter-row positions was increased between Bed and Ridge profiles following irrigation, since more water was shed from the flanks of Ridge profiles into the furrows than in Bed profiles leaving the ridge center drier than in Bed profiles (Table 38). The soil wetting pattern that resulted following irrigation was slightly more homogeneous at the later irrigation event than the earlier one. Both irrigation events highlight the advantages in Bed profiles in maintaining a more homogeneous soil water distribution than Ridge profiles. The high water content (19.8-24.1 % volumetric) measured in furrows following irrigation in Ridge profile plantings exceeded the Field Capacity of the sand soil in the field (typically 17 % volumetric), and therefore would be lost to gravitational flow.

Position	Profile	Bed		Ridge		S.E.
Row centre	Hood pressure	Minimum	Maximum	Minimum	Maximum	(14 D.F.)
Pre-irrigation	Shallow destoning	13.3	14.1	12.0	12.5	0.46
	Deep destoning	13.5	14.1	12.5	12.7	
Post-irrigation	Shallow destoning	21.5	23.4	21.2	20.1	0.70
	Deep destoning	23.2	23.0	19.5	21.2	
Diff. post-pre	Shallow destoning	8.2	9.2	9.3	7.6	0.76
	Deep destoning	9.8	8.9	7.1	8.5	
Furrow						
Pre-irrigation	Shallow destoning	14.0	15.0	14.7	15.2	0.46
	Deep destoning	14.0	14.8	16.0	15.7	
Post-irrigation	Shallow destoning	22.7	22.6	25.7	25.1	0.51
	Deep destoning	23.1	22.3	25.7	25.2	
Diff. post-pre	Shallow destoning	8.7	7.6	11.0	10.0	0.75
	Deep destoning	9.1	7.5	9.7	9.4	
Diff. furrow-row						
Pre-irrigation	Shallow destoning	0.8	0.9	2.7	2.7	0.33
	Deep destoning	0.5	0.7	3.5	3.1	
Post-irrigation	Shallow destoning	1.2	-0.8	4.4	5.0	0.64
	Deep destoning	-0.1	-0.7	6.2	4.0	
Diff. post-pre	Shallow destoning	0.4	-1.6	1.8	2.4	0.71
	Deep destoning	-0.7	-1.4	2.7	0.8	

TABLE 38. MEASUREMENTS AND CHANGES IN SOIL WATER CONTENT (% VOLUMETRIC) FOLLOWING IRRIGATION OF 25 MM ON 14 JULY IN EXPT 2009C

4.4.3. Tuber yield and dry matter concentration

The final harvest was taken on 1 October. There were no significant effects of treatments on the total number of tubers > 10 mm (468 000 ± 14 300/ha, equivalent to 3.4 tubers per stem). Total yield (and yield > 40 mm) was greater where destoning was carried out deeper, where the crop was grown in Ridge rather than Bed profiles and where the ridge/bed was not compressed excessively at planting (Table 39). The mean effect of planting in Ridge compared with Bed profile was c. 6.2 t/ha, similar to the difference between using Minimum compression and Maximum on the covering hood. The yield loss from destoning at only 20 cm depth compared with 35 cm was c. 7.2 t/ha.

Profile	Bed		Ridge	
Hood pressure	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Tuber fresh weight yield				
Shallow destoning	57.4	52.4	63.6	60.5
Deep destoning	68.0	58.0	71.5	65.1
S.E. (14 D.F.)	3.82			
Dry matter concentration				
Shallow destoning	24.8	25.0	25.0	25.5
Deep destoning	24.2	24.4	23.6	24.5
S.E. (14 D.F.)	0.14			
Tuber dry weight yield				
Shallow destoning	13.6	12.3	15.2	14.8
Deep destoning	16.1	13.6	16.5	15.4
S.E. (14 D.F.)	0.95			

TABLE 39. TOTAL (> 10 MM) TUBER FRESH WEIGHT AND DRY WEIGHT YIELDS (T/HA) AND DRY MATTER CONCENTRATION (%) ON 1 OCTOBER IN EXPT 2009C

Tuber dry matter concentration was c. 24-25 %, which is much higher than normally expected in Rooster and above the limit that would be regarded as safe with respect to cooking breakdown (William Jackson, Albert Bartlett & Sons Ltd, personal communication). September 2009 was almost completely devoid of rainfall and irrigation had clearly stopped well before final harvest on 1 October. On average, Shallow destoning and Maximum pressure ridge/bed compression increased tuber dry matter concentration by 0.9 and 0.4 % (absolute), respectively, compared with Deep destoning and Minimum pressure (Table 39). Destoning shallowly and growing in Ridge profiles increased tuber dry matter yield by 1.4-1.6 t/ha, respectively, compared with Deep destoning and Bed profiles. Although not quite significant, the difference in dry weight yield between Minimum and Maximum pressure was in the same direction as for fresh weight yield (Table 39).

4.4.4. Common scab

The incidence of common scab was very low, with only 20 % of tubers with > 1 % surface area infected with scab and < 5 % of tubers with > 5 % surface area. The mean surface area infected was 1.8 %. Despite differences in soil bulk density, water content and infiltration distribution, there was no effect of any treatment on common scab incidence.

4.5. Experiment 2010a

4.5.1. Soil water content at cultivation

In mid-March, the soil was at Field Capacity (c. 27 % volumetric) following a winter with significant rain and snowfall. The Plough Early treatments would therefore mimic most commercial spring-ploughing. Once ploughed, these plots were rototilled within 1 hour and the water content of soil at maximum rototiller depth was drier than at the equivalent depth in undisturbed stubble (Table 40). The Late cultivation plots were 3.3-4.3 % (absolute) drier at cultivation depth for rotoridging than the Early-cultivated plots. However, for the Late treatments, there was a longer interval (8 days) between the first primary cultivation (i.e. plough or Progressive) and rotary ridging which allowed large unweathered clods to dry. The Late Non-plough cultivation dried most appreciably after the final primary cultivation at 30 cm but there was little drying when cultivated at 15 and 20 cm (Table 40).

Date	Operation		Treatment	Soil water content	S.E.
16 March	Plough		Plough Early	26.9	0.91
16 March	Rototiller		Plough Early	24.2	0.80
16 March	Rototiller		Non-plough Early	27.2	0.70
6 April	Plough		Plough Late	27.4	0.75
6 April	Progressive 15 cm	@	Non-plough Late	27.9	0.41
8 April	Progressive 20 cm	@	Non-plough Late	26.5	0.98
13 April	Progressive 30 cm	@	Non-plough Late	26.4	2.39
14 April	Rototiller		Plough Late	22.8	1.14
14 April	Rototiller		Non-plough Late	23.8	1.41

TABLE 40. SOIL WATER CONTENT (% VOLUMETRIC) AT 25 CM DEPTH AT VARIOUS OPERATIONS IN EXPT 2010A

4.5.2. Soil properties

4.5.2.1. Textural analysis

The average soil texture was a clay loam but with lower clay content in the middle of the experimental area than at either end (Table 41). The average volumetric stone content (>2mm) taken from bulk density sampling was moderate (11.6± 3.46 %).

	Sand			Silt	Clay	Textural
	Coarse	Medium	Fine			Classification
Plot 1-1	0	39	6	29	26	Clay loam
Plot 1-8	0	44	4	26	26	Clay loam
Plot 2-1	1	44	6	27	22	Sandy clay loam
Plot 2-8	0	43	8	26	23	Sandy clay loam
Plot 3-1	1	40	4	28	27	Clay loam
Plot 3-8	1	43	4	27	25	Clay loam
Mean	1	42	5	27	25	Clay loam
S.E. (5 D.F.)	0.5	2.1	1.6	1.2	1.9	

TABLE 41. PROPORTIONS OF SAND, SILT AND CLAY (% GRAVIMETRIC) WITHIN THE EXPERIMENTAL AREA IN EXPT 2010A

4.5.2.2. Bulk density and porosity

Soil bulk densities throughout the profile were similar to those found in 2007-2009 but were lower in the 25-30 cm horizon (1.26 g/cm3) in 2010 than in 2007-2009 (1.32 g/cm3). Bulk density in the top 20 cm of the profile was unaffected by cultivation regime in 2010. Between 20 and 30 cm depth, Early Non-plough cultivation resulted in higher bulk densities than Late Non-plough (Figure 44a). There was no significant effect of date of ploughing on bulk density. The rototilling was carried out at a depth of 25 cm whereas ploughing and the deepest Progressive cultivations were conducted at c. 30 cm which would have loosened soil 5 cm deeper than Non-plough Early cultivation and this was reflected by the lower bulk densities at 25-30 cm measured in Plough Early and Non-plough Late although the Plough Late was not significantly lower than Non-plough Early at this depth. Total pore space and air capacity, unsurprisingly, showed the reverse of bulk density, with Early Non-plough treatments having less porosity and air capacity than Late Non-plough at 20-25 cm depth (Figure 44b,c). There was no effect of timing within Plough treatments at this depth. Between 25 and 30 cm (the tine or share depth for plough or Progressive cultivation), Early ploughing resulted in more porous soil than Late ploughing (Figure 44b) and Early ploughing increased air capacity in this profile compared with Late plough and Non-plough cultivation (Figure 44c).

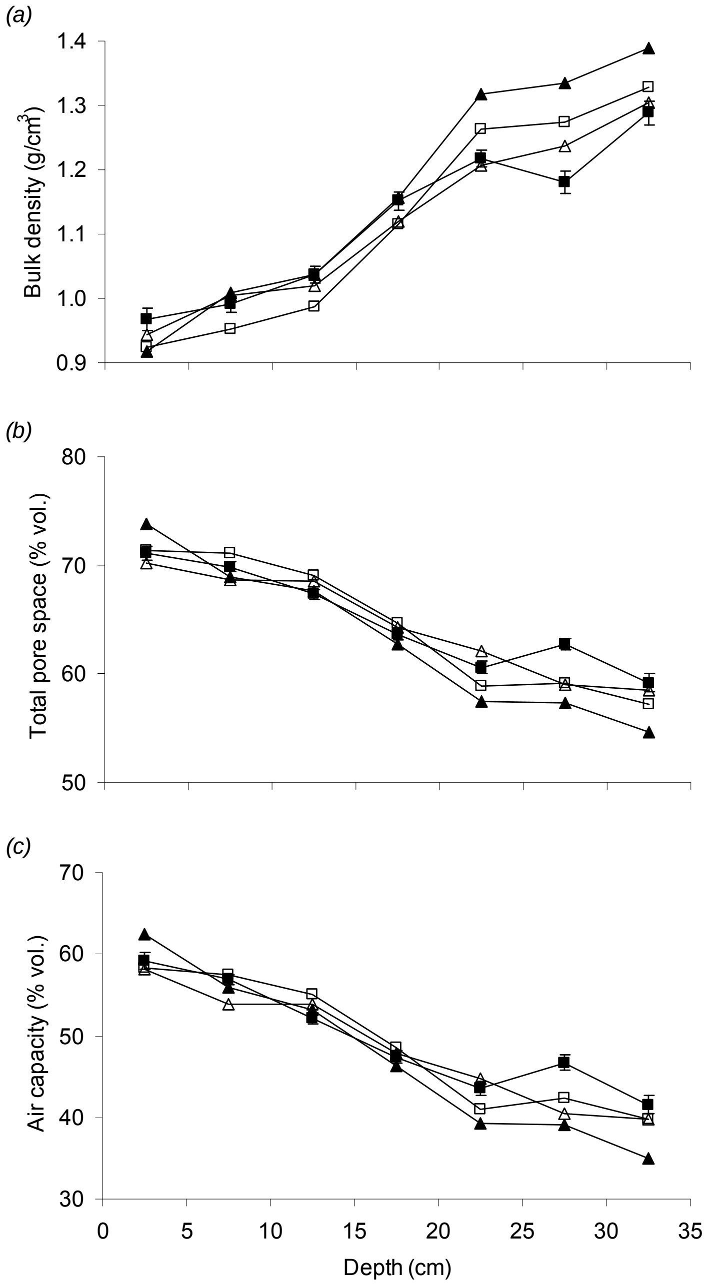

FIGURE 44. EFFECTS OF CULTIVATION REGIME ON (A) SOIL BULK DENSITY, (B) POROSITY AND (C) AIR CAPACITY IN EXPT 2010A. CULTIVATION REGIME: PLOUGH EARLY ■; PLOUGH LATE □; NON-PLOUGH EARLY, ▲; NON-PLOUGH LATE, △. S.E. BASED ON 14 D.F.

The overall ridge bulk density at emergence was greater for Late cultivation than Early, irrespective of method (Table 42). However, by 12 August, ridge bulk density had increased in Early-timed cultivation treatments such that there was no significant difference between any cultivation regime. There was no further change in bulk density between 12 August and final harvest. Prolonged exposure of bare ridges to irrigation often results in an increase in ridge bulk density. Despite the large differences in canopy cover resulting from varieties with contrasting determinacies and nitrogen rates, bulk density was unaffected by these treatments.

	Cultivation regime				
	Plough Early	**Plough Late**	**Non-plough Early**	**Non-plough Late**	**S.E. (14 D.F.)**
28 May	0.95	0.99	0.94	0.99	0.017
12 August	1.00	0.95	0.99	0.99	0.018
28 September	0.98	1.00	0.97	1.00	0.015

TABLE 42. RIDGE BULK DENSITY ON 28 MAY, 12-13 AUGUST AND 28 SEPTEMBER IN EXPT 2010A. MEAN OF BOTH VARIETIES AND NITROGEN RATES

4.5.3. Resistance

Penetrometer readings were first taken the day after planting. Resistances within the subsoil were generally lower than in previous years. Cultivating Early only with the rototiller resulted in a higher resistance between 25 and 30 cm than other cultivation regimes (Figure 45a). Whilst not significant, Early ploughing tended to decrease resistance between 25 and 30 cm compared with Late ploughing. There was little change in resistance between April and July, perhaps as the crop was well irrigated which maintained wet soil at depth, but the relative differences in resistance between cultivation treatments observed at planting gradually reduced as the season progressed (Figure 45b,c).

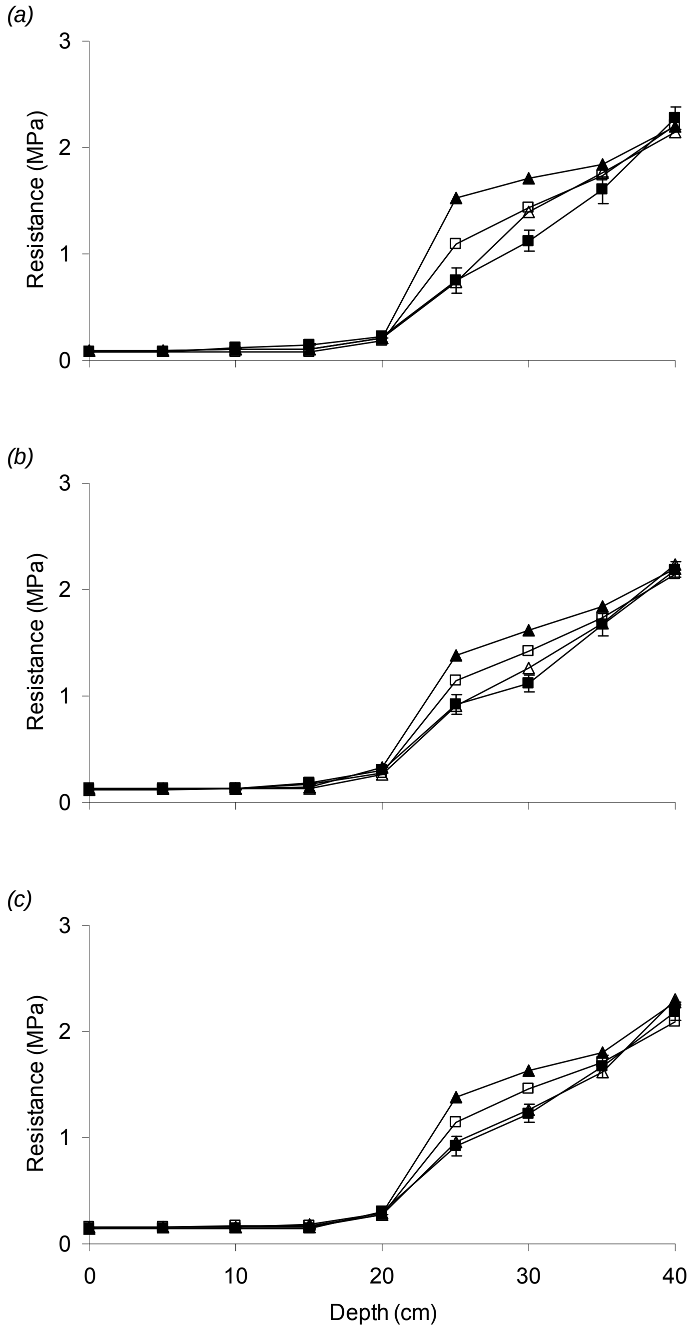

FIGURE 45. PENETRATION RESISTANCE ON *(A)* 19 APRIL; *(B)* 8 JUNE AND *(C)* 23 JULY IN EXPT 2010A. CULTIVATION REGIME: PLOUGH EARLY ■; PLOUGH LATE □; NON-PLOUGH EARLY, ▲; NON-PLOUGH LATE, △. S.E. BASED ON 14 D.F.

4.5.3.1. Water holding capacity

The quantity of very easily available water held at tensions < 60 kPa on both a gravimetric (g/g) and volumetric basis (cm3/cm3) at 25-30 cm depth was not significantly affected by any cultivation treatment but was numerically least on a volumetric basis in Early Plough and Late Non-plough as these treatments had a higher porosity at 25-30 cm depth than the other cultivation regimes (Table 43). Numerically, withholding cultivation below 25 cm at planting (Non-plough Early) resulted in the greatest quantity of water held per unit volume of soil but this needs to be balanced against the potential restriction in rooting as a consequence of higher soil resistance at 25 cm in the Early Non-plough treatment.

	Cultivation regime				
	Plough Early	**Plough Late**	**Non-plough Early**	**Non-plough Late**	**S.E. (6 D.F.)**
Gravimetric (%)	20.5	20.9	20.1	21.4	0.70
Volumetric (%)	25.5	27.4	29.6	25.5	1.22

TABLE 43. EASILY AVAILABLE WATER HOLDING CAPACITY (60 KPA) ON 28 MAY IN EXPT 2010A. MARIS PIPER, 180 N PLOTS ONLY.

4.5.3.2. Soil moisture deficits

Irrigation was scheduled based on the ground covers of the Maris Piper Plough Late 180N treatments and the maximum SMD did not exceed 27 mm and was therefore kept under the target Allowable SMD of 30 mm. Until the end of August, there were no overall differences between cultivation regimes in the patterns or magnitudes of the modelled SMDs as the ground covers were very similar (see later section), however in Maris Piper crops, the Non-plough Late treatments developed higher SMDs during September than Plough Late or Non-plough Early (Figure 46). Applying no nitrogen fertilizer reduced the maximum SMD attained from 35 to 30 mm compared with 180N treatments and overall accumulated SMD was less in 0N treatments than in 180N.

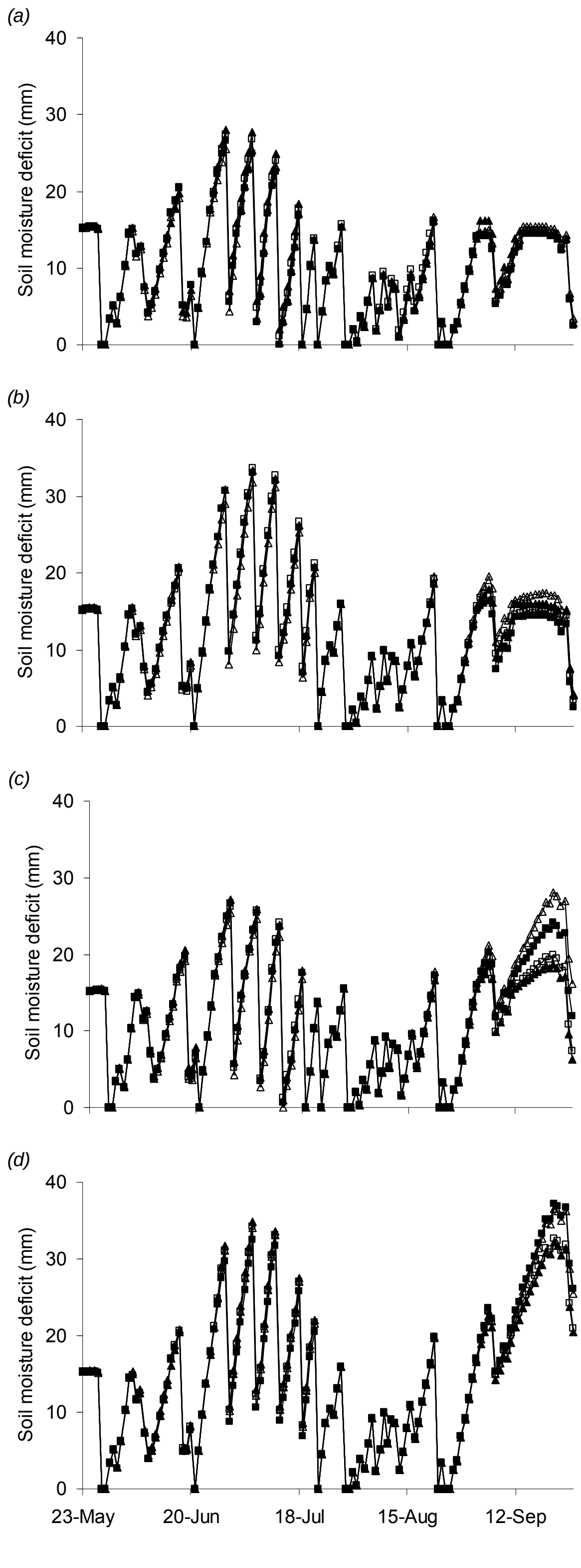

FIGURE 46. SOIL MOISTURE DEFICITS IN (A) LADY ROSETTA 0N; (B) LADY ROSETTA 180 N; (C) MARIS PIPER 0N; (D) MARIS PIPER 180N IN EXPT 2010A. CULTIVATION REGIME: PLOUGH EARLY ■; PLOUGH LATE □; NON-PLOUGH EARLY, ▲; NON-PLOUGH LATE, △. S.E. BASED ON 16 D.F.

4.5.3.3. *Ped size distribution*

At emergence, there was a greater proportion of peds > 15 mm in Late cultivation than Early, particularly the largest ped sizes in Late Non-ploughed (Figure 47). Conversely, Early cultivation resulted in 48 % of the ridge being comprised of ped < 6 mm diameter compared with only 35 ± 3.3 % in Late cultivated plots. Mean ped size was smaller for Early cultivation than Late but Late Non-ploughed treatments had a much larger average ped size than Early Non-ploughed (Table 44). The same treatment differences in distribution of ped sizes were observed at final harvest but there was an increase in the proportion of peds > 6 mm compared with the soil at emergence owing to degradation of peds through weathering. The greatest reduction in mean ped size during the season was in the Non-plough Late treatment which had the greatest proportion of the largest ped sizes at emergence (Table 44).

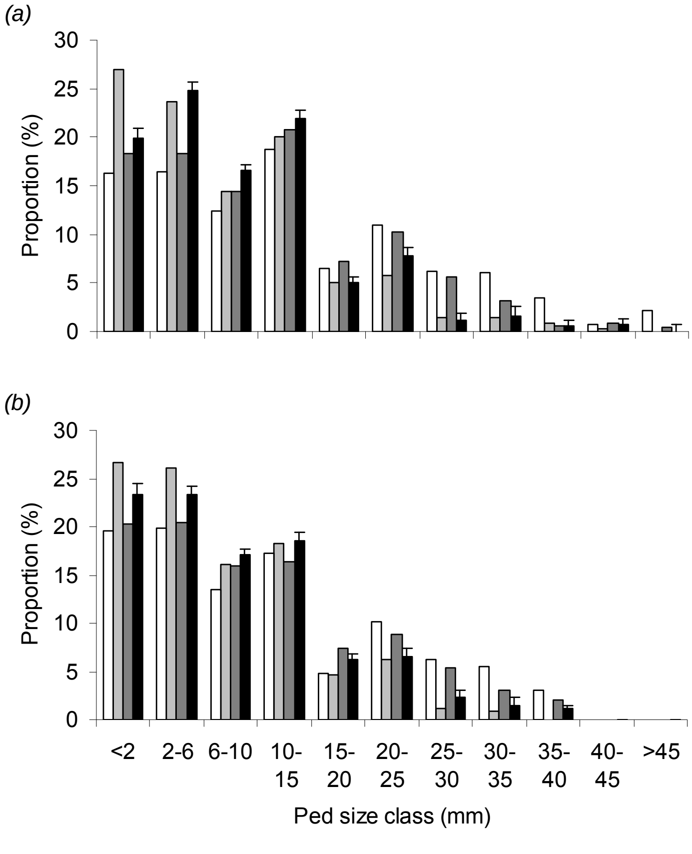

FIGURE 47. PED SIZE DISTRIBUTION ON (A) 28 MAY AND (B) 28 SEPTEMBER IN EXPT 2010A. CULTIVATION REGIME: PLOUGH EARLY ■; PLOUGH LATE ■; NON-PLOUGH EARLY, ■; NON-PLOUGH LATE, □. MEAN OF BOTH VARIETIES AND NITROGEN RATES. S.E. BASED ON 14 D.F.

	Cultivation regime				S.E.
	Plough Early	Plough Late	Non-plough Early	Non-plough Late	(14 D.F.)
28 May	9.2	11.6	8.4	14.0	0.53
28 September	8.9	10.9	7.7	12.0	0.50

TABLE 44. MEAN PED SIZE (MM) IN RIDGE ON 28 MAY AND 28 SEPTEMBER IN EXPT 2010A. MEAN OF BOTH VARIETIES AND NITROGEN RATES

4.5.4. Plant measurements

4.5.4.1. Emergence, ground covers and radiation absorption

The average date of 50 % plant emergence was 24 May (35 days after planting). Both Lady Rosetta and Maris Piper achieved 50 % emergence on the same date but, on average, the date of 50 % emergence was delayed by 1 day when no N was applied and was also delayed by c. 1 day in the Late Plough and Non-plough areas. Initial ground cover expansion was slowed when no N was applied, so that at 25 DAE the average ground cover was 37 % when no N was applied and 53 % when 180 kg N/ha had been applied (Figure 48). In the absence of N fertilizer, maximum ground cover was significantly smaller when compared with plots receiving 180 kg N/ha. However, maximum ground cover was not significantly affected by either variety or cultivation regime. The mean, season-long integrated ground cover was 7302 % days and this was not affected significantly by cultivation regime. On average, the integrated ground cover of Lady Rosetta was smaller than that of Maris Piper (6318 compared with 8287 % days) and was also smaller when no N was applied than where the application rate was 180 kg N/ha (5964 and 8641 % days, respectively). More solar radiation was absorbed by Maris Piper (12.60 TJ/ha) than Lady Rosetta (10.45 TJ/ha) and increasing the N application rate from 0 to 180 kg N/ha increased radiation absorption from 9.53 to 13.53 TJ/ha. The cultivation treatments had no significant on radiation absorption by the crop in either variety.

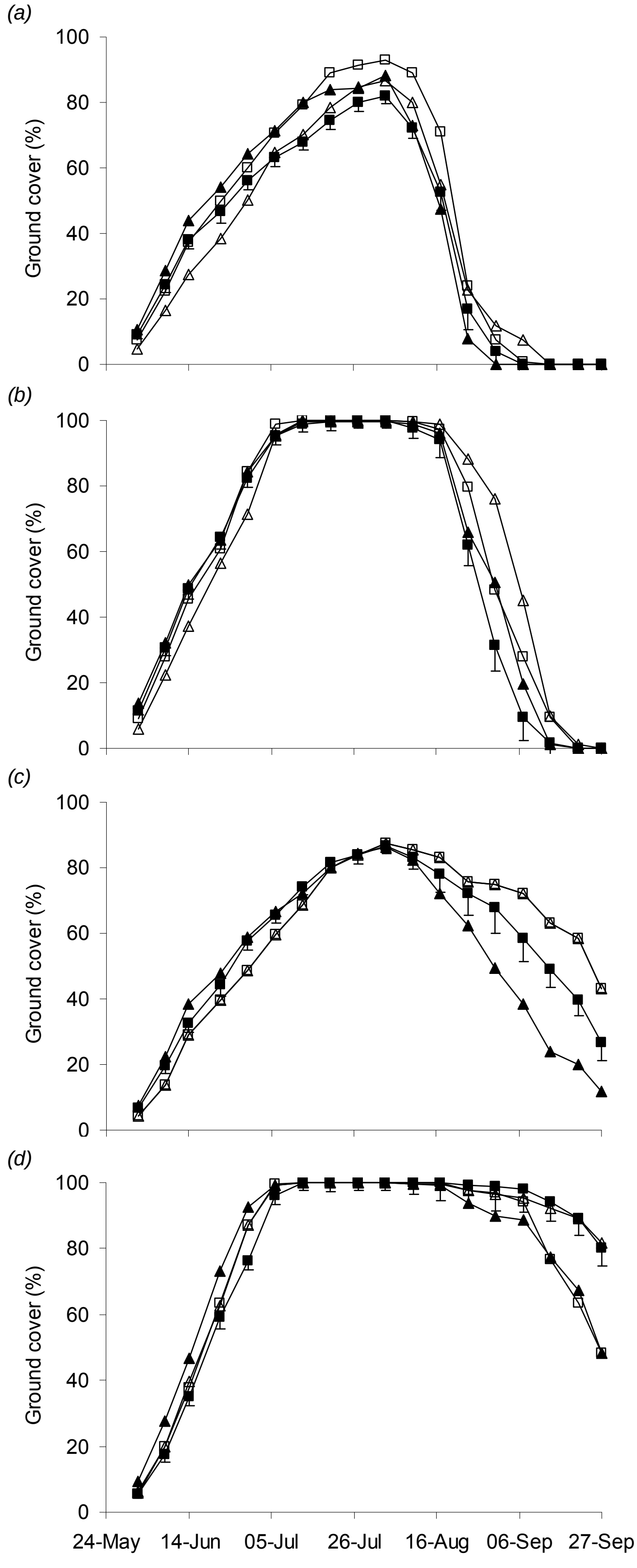

FIGURE 48. EFFECT OF CULTIVATION REGIME, VARIETY AND RATE OF NITROGEN FERTILIZER ON GROUND COVER. (*A*) LADY ROSETTA 0N; (*B*) LADY ROSETTA 180N; (*C)* MARIS PIPER 0N; (*D*) MARIS PIPER 180N IN EXPT 2010A. CULTIVATION REGIME: PLOUGH EARLY ■; PLOUGH LATE □; NON-PLOUGH EARLY, ▲; NON-PLOUGH LATE, △. S.E. BASED ON 16 D.F.

Variety	N	Cultivation	GC at 25 DAE (%)	Integrated GC (% days)	Radiation absorbed (TJ/ha)
Lady Rosetta	0	Plough Early	38	5383	9.13
		Plough Late	40	5555	9.28
		Non-plough Early	43	5176	8.87
		Non-plough Late	33	4894	8.10
Mean			39	5252	8.85
Lady Rosetta	180	Plough Early	54	7204	11.98
		Plough Late	54	7629	12.48
		Non-plough Early	53	7513	12.42
		Non-plough Late	51	7761	12.46
Mean			53	7527	12.34
Maris Piper	0	Plough Early	36	7083	10.82
		Plough Late	35	6442	10.08
		Non-plough Early	37	6429	10.17
		Non-plough Late	32	8171	12.13
Mean			35	7031	10.80
Maris Piper	180	Plough Early	48	9831	14.60
		Plough Late	54	9537	14.53
		Non-plough Early	56	9711	14.92
		Non-plough Late	54	9943	14.89
Mean			53	9755	14.73
S.E. Var*N (16 D.F.)			1.6; 2.0†	226.4; 343.8†	0.415; 0.490†
S.E. Var*Cult*N (16 D.F.)			3.1; 4.0‡	452.8; 486.1‡	0.587; 0.692‡

TABLE 45. EFFECT OF VARIETY, N APPLICATION RATE AND CULTIVATION REGIME ON GROUND COVER 25 DAYS AFTER EMERGENCE (DAE) MAXIMUM GROUND COVER (PERCENT AND ANGULAR TRANSFORMED), WHOLE-SEASON INTEGRATED GROUND COVER AND RADIATION ABSORPTION IN EXPT 2010A

4.5.4.2. Number of stems, tuber and tuber fresh weight (FW) yields

When averaged over all harvests, cultivation and N application rates, Lady Rosetta had a stem population of 165 000/ha compared with 120 000/ha for Maris Piper (Table 46). For both varieties, stem populations were reasonably consistent at each harvest. The first sample was taken on 14 June (c. 21 DAE) during tuber initiation and the mean tuber population > 10 mm at this harvest was smaller when compared with mean tuber populations measured later in the season. When compared with Lady Rosetta, the tuber population of Maris Piper was smaller at all harvests. Numerically, tuber populations were also smaller when no N fertilizer was applied but this effect was only significant at harvests on 22 July and 23 August. Main effects of cultivation regime on tuber populations were significant but inconsistent between harvests. At the first harvest, the Non-plough Early treatment had the largest tuber population but at all subsequent samplings this treatment had the smallest tuber population. This discrepancy may due to this cultivation treatment achieving 50 % emergence 1-2 days before the others and thus having a larger tuber population at the earliest harvest.

	14 June		22 July		23 August		27 September	
	Stems	**Tubers**	**Stem**	**Tuber**	**Stems**	**Tubers**	**Stems**	**Tubers**
Plough Late	140	286	137	656	145	625	142	648
Plough Early	141	288	136	704	141	656	133	642
Non-plough Late	150	289	144	690	156	681	141	620
Non plough Early	144	445	144	599	142	561	146	582
S.E. (14 D.F.)	4.4	27.0	5.1	19.0	5.5	16.7	3.0	13.3
Lady Rosetta	169	480	161	717	167	700	162	676
Maris Piper	119	175	119	608	125	561	119	569
S.E. (16 D.F.)	3.5	12.3	3.5	11.8	4.2	12.3	2.7	16.9
0 kg N/ha	143	311	139	641	139	592	142	613
180 kg N/ha	144	344	141	684	153	669	139	633
S.E. (14 D.F.)	3.1	19.1	3.6	13.5	3.9	11.8	2.2	9.4

TABLE 46. MAIN EFFECTS OF CULTIVATION REGIME. VARIETY AND N RATE ON STEM AND TUBER POPULATION > 10 MM (000/HA) IN EXPT 2010A

At the first sampling, the tuber FW yield of Lady Rosetta (2.5 t/ha) was significantly larger than the yield of Maris Piper (0.8 t/ha). The tuber yield of the Non-plough Early treatment was significantly larger than the other cultivation treatments but this may have been consequence of this cultivation treatment emerging slightly early than the others. At the second sampling (22 July), the yields of the Non-plough Early treatments were larger than in the Non-plough Late but the effect was quite small (Table 47) and, on average, Lady Rosetta had a larger yield than Maris Piper. When compared to no N, applying 180 kg N/ha increased yields by c. 4.5 t/ha but this response to N was much larger in Lady Rosetta than in Maris Piper. At the third sampling, the cultivation treatments had no effect on yield and the varietal differences in tuber yields were also small and not statistically significant. The response to N in Lady Rosetta was to increase yield by 17.6 t/ha, whereas in Maris Piper the response was smaller (12.8 t/ha). The final sampling was taken at the end of September when the canopies of Lady Rosetta had completely senesced but the canopies of Maris Piper were still between 15 and 85 % ground cover. Whilst the cultivation treatments had no effect on tuber yield, the yield of Maris Piper was significantly larger than that of Lady Rosetta. Between the third and final sampling, the average yield of Lady Rosetta increased by 3.5 t/ha whereas the yield of Maris Piper increased by 9.4 t/ha. When averaged over both varieties, the response to 180 kg N/ha was 20.5 t/ha and the response to N was similar in each individual variety.

	14 June	22 July	23 August	27 September
Plough Early	1.4	29.5	47.3	53.1
Plough Late	1.4	28.7	49.5	55.5
Non-plough Early	2.8	29.8	47.6	54.6
Non-plough Late	1.3	26.5	47.2	53.1
S.E. (14 D.F.)	0.20	0.50	1.18	1.26
Lady Rosetta	2.5	30.6	48.8	51.7
Maris Piper	0.8	26.3	47.0	56.4
S.E. (16 D.F.)	0.07	0.47	0.63	1.27
0 kg N/ha	1.5	26.3	40.3	43.8
180 kg N/ha	1.9	30.9	50.5	64.3
S.E. (14 D.F.)	0.14	0.35	0.83	0.88
Lady Rosetta 0 kg N/ha	2.2	27.2	40.0	42.4
Lady Rosetta 180 kg N/ha	2.8	34.0	57.6	61.1
Maris Piper 0 kg N/ha	0.7	25.4	40.6	45.3
Maris Piper 180 kg N/ha	0.9	27.8	53.4	67.4
S.E. (16 D.F., same N level)	0.10	0.66	0.89	1.79
S.E. (16 D.F., different N levels)	0.16	0.58	1.04	1.55

TABLE 47. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON TUBER FW YIELD > 10 MM (T/HA) IN EXPT 2010A

4.5.4.3. Tuber DM concentration, total DM yield, radiation use efficiency and onset of bulking

Tuber dry matter concentration was unaffected by cultivation regime at any harvest. Lady Rosetta had a higher dry matter concentration than Maris Piper throughout, although the difference at final harvest was small (Lady Rosetta 25.5%, Maris Piper 24.8 % ± 0.17%, Figure 49). At the second harvest, applying 180 kg N/ha reduced dry matter concentration compared with no applied N. By the penultimate harvest in August, there was no effect of N rate in Lady Rosetta but unfertilized Maris Piper still had a higher dry matter concentration than fertilized. There was no overall effect of N at the final harvest in either variety.

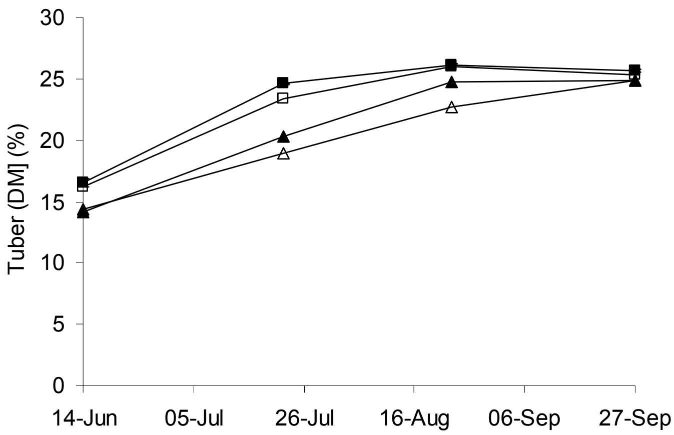

FIGURE 49. TUBER DRY MATTER CONCENTRATION [DM] IN EXPT 2010A. CULTIVATION REGIME: LADY ROSETTA 0N ■; LADY ROSETTA 180N □; MARIS PIPER 0N, ▲; MARIS PIPER 180N, △. MEAN OF ALL CULTIVATION REGIMES. S.E. BASED ON 16 D.F.

At the final sampling, cultivation regime had no effect on total DM production (Table 48). When averaged over the other treatments, DM production in Maris Piper was c. 2.2 t/ha larger than in Lady Rosetta. In Lady Rosetta, the response to 180 kg N/ha was 5.3 t/ha whilst in Maris Piper the response was 7.2 t/ha. These treatment differences are consistent with their effects on canopy persistence and radiation absorption (Table 45). Average, season-long, radiation use efficiency (RUE) was 1.40 t DM/TJ and was similar to that found for irrigated crops in Expt 2009a. Radiation use efficiency was not significantly affected by cultivation regime, variety or N application rate. In the 2009 experiment RUE was influenced by planting date and irrigation but was not affected by the contrasting cultivation treatments.

The average interval between 50 % plant emergence and the apparent onset of tuber bulking was c. 19 days. Cultivation regime had no significant effect on the onset of bulking but, on average, bulking was c. 7 days earlier in Lady Rosetta than in Maris Piper and was delayed by 6 days when the N application rate was increased from 0 to 180 kg N/ha. The effect of N on bulking was also affected by variety: the delay was c. 3 days in Lady Rosetta and c. 9 days in Maris Piper. The start of tuber bulking in Maris Piper given 180 kg N/ha (27 DAE) was similar to that found in Expt 2009a.

	Total DM yield on 27 September (t/ha)	Radiation use efficiency (t DM/TJ)	Start of tuber bulking (DAE)
Plough Early	15.23	1.42	19.6
Plough Late	15.79	1.44	20.0
Non-plough Early	15.18	1.34	18.9
Non-plough Late	15.36	1.41	18.0
S.E. (14 D.F.)	0.422	0.030	1.10
Lady Rosetta	14.31	1.44	15.7
Maris Piper	16.47	1.37	22.5
S.E. (16 D.F.)	0.389	0.029	0.97
0 kg N/ha	12.27	1.37	16.2
180 kg N/ha	18.51	1.43	22.0
S.E. (14 D.F.)	0.298	0.021	0.78
Lady Rosetta 0 kg N/ha	11.68	1.40	14.3
Lady Rosetta 180 kg N/ha	16.95	1.47	17.2
Maris Piper 0 kg N/ha	12.87	1.34	18.0
Maris Piper 180 kg N/ha	20.07	1.39	26.9
S.E. (16 D.F., same N level)	0.550	0.041	1.37
S.E. (16 D.F., different N levels)	0.490	0.036	1.24

TABLE 48. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON TOTAL DM PRODUCTION, RADIATION USE EFFICIENCY AND THE APPARENT START OF TUBER BULKING IN EXPT 2010A

4.5.4.4. Nitrogen uptake and redistribution

The effects of the treatments on total N uptake at each sampling are shown in Table 49. Irrespective of treatment, c. 85 % of the total crop N uptake had occurred by the second sampling on 22 July (c. 59 DAE) and this is consistent with many other observations on the pattern of total N uptake by potato crops. At the first sampling, total N uptake differed by 14 kg N/ha between the Plough Early and Non-plough Early treatments and total N uptake was 11 kg N/ha larger for Lady Rosetta than for Maris Piper. Increasing the N uptake from 0 to 180 kg N/ha increased total N uptake by c. 31 kg N/ha. At the second sampling neither cultivation nor variety had any effect on total N uptake but N uptake was increased by 105 kg N/ha in response to an application of 180 kg N/ha. At the penultimate sampling on 23 August, increasing the N application rate from 0 to 180 kg N/ha increased total N uptake by 131 kg N/ha representing a fertilizer N recovery of c. 73 %. Total N uptakes by Lady Rosetta and Maris Piper were similar and N uptake was not affected by cultivation regime. At the final harvest at the end of September, neither cultivation nor variety had any effect on total N uptake but increasing the N application rate from 0 to 180 kg N/ha increased total N uptake from 124 to 245 kg N/ha.

	14 June	22 July	23 August	27 September
Plough Early	45	172	189	182
Plough Late	51	168	207	190
Non-plough Early	59	166	186	183
Non-plough Late	48	160	190	185
S.E. (14 D.F.)	1.8	6.1	5.8	5.2
Lady Rosetta	56	166	192	182
Maris Piper	45	167	194	187
S.E. (16 D.F.)	0.9	4.4	4.0	5.3
0 kg N/ha	35	114	128	124
180 kg N/ha	66	219	258	245
S.E. (14 D.F.)	1.2	4.3	4.1	3.7
Lady Rosetta 0 kg N/ha	39	113	127	125
Lady Rosetta 180 kg N/ha	74	219	257	240
Maris Piper 0 kg N/ha	32	115	128	124
Maris Piper 180 kg N/ha	58	219	259	251
S.E. (16 D.F., same N level)	1.3	6.2	5.7	7.4
S.E. (16 D.F., different N levels)	1.5	6.2	5.7	6.4

TABLE 49. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON TOTAL (HAULM AND TUBER) N UPTAKE (KG N/HA) ON FOUR OCCASIONS IN EXPT 2010A

Haulm N uptake was not affected by the contrasting cultivations nor by variety (Table 50) but when the amount of N applied was increased from 0 to 180 kg N/ha, maximum haulm N uptake increased from 66 to 144 kg/ha. This increase was similar in both Lady Rosetta and Maris Piper. For similar N treatments, maximum haulm N uptakes were larger in 2010 than in 2009. A key date in a crop's development is the date after emergence at which the rate of N uptake by the tubers (which is approximately constant with respect to absorbed radiation) becomes equal to the rate of total N uptake (which is initially rapid but steadily decreases). After this date the crop canopy becomes a net exporter of N and canopy senescence will follow. This date was not affected in 2010 by N application rate or cultivation but differed by c. 8 days between the varieties. The rate of tuber N uptake dictates how quickly reserves of N held in the canopy are depleted and thus when the canopy will be completely senesced. The rate of N uptake was significantly faster in Lady Rosetta than Maris Piper and was also faster when N was applied than where it was withheld completely.

	Rate of tuber N uptake (kg N/TJ)	Maximum total N uptake (kg N/ha)	Maximum haulm N uptake (kg N/ha)	Rate of total and tuber N uptake equal (DAE)
Plough Early	14.3	188	106	44
Plough Late	14.6	203	106	46
Non-plough Early	13.7	188	100	43
Non-plough Late	13.7	191	107	47
S.E. (14 D.F.)	0.32	3.8	4.5	1.0
Lady Rosetta	15.9	190	99	41
Maris Piper	12.3	194	111	49
S.E. (16 D.F.)	0.24	5.5	5.4	1.4
0 kg N/ha	11.7	131	66	45
180 kg N/ha	16.5	254	144	45
S.E. (14 D.F.)	0.23	2.7	3.2	0.7
Lady Rosetta 0 kg N/ha	13.3	132	61	41
Lady Rosetta 180 kg N/ha	18.5	249	137	42
Maris Piper 0 kg N/ha	10.1	130	71	50
Maris Piper 180 kg N/ha	14.5	258	150	48
S.E. (16 D.F., same N level)	0.36	7.8	7.6	2.0
S.E. (16 D.F., different N levels)	0.33	6.1	6.2	1.6

TABLE 50. EFFECTS OF CULTIVATION, VARIETY AND N APPLICATION RATE ON RATE OF TUBER N UPTAKE, MAXIMUM TOTAL AND HAULM N UPTAKE AND DATE WHEN RATE OF TOTAL N AND TUBER N UPTAKE ARE EQUAL IN EXPT 2010A

4.5.4.5. Common scab and growth cracking

The incidence of common scab was very high with > 99 % of tubers infected and a high overall severity (25.6 % surface area infected). Irrigation was not scheduled for common scab in the 4 weeks after tuber initiation, with the SMD increasing to c. 21 mm 5 days after initiation and c. 31 mm around 2 weeks later. Despite this, the Early cultivation regimes had a lower incidence and severity of scab than Late (Table 51), consistent with smaller mean ped size within the ridge (Table 44) but unlike the data from Expts 2008 and 2009a where differences in ridge cloddiness between treatments were as great. The incidence of tuber growth cracking was low and not affected by cultivation regime (Table 51).

Cultivation	Scab incidence < 5 % SA (%)	Ang.† scab incid. < 5 % SA	Scab severity (% SA)	Growth crack incidence (%)	Ang.† growth crack incidence
Plough Early	11.1	19.4	22.9	1.9	4.1
Plough Late	7.8	10.9	28.4	2.1	4.4
Non-plough Early	13.4	23.2	20.6	2.6	5.9
Non-plough Late	2.6	4.6	30.3	2.7	6.4
S.E. (14 D.F.)	-	5.26	2.77	-	1.99

†Angular transformation

TABLE 51. INCIDENCE AND SEVERITY (% SURFACE AREA, SA) OF COMMON SCAB AND INCIDENCE OF GROWTH CRACKING (MARIS PIPER TREATMENT ONLY) IN EXPT 2010A

4.6. Experiment 2010b

4.6.1. Emergence and tuber initiation

There was only one day difference in date of 50 % plant emergence for Maris Piper (22 May) and Vales Sovereign (23 May) but there was a more protracted period from 10-90 % emergence in Vales Sovereign (13 days) than Maris Piper (6 days). Both varieties commenced tuber initiation 19 days after initial emergence, with the date of 50 % initiation being 17 days after 50 % emergence. The period from first observed initiation to 95 % of plants initiated was short: 5 days for Maris Piper and 7 days for Vales Sovereign.

4.6.2. Ground cover

The initial rate of ground cover development was faster in Maris Piper than Vales Sovereign, with full canopy cover in the most advanced irrigation treatments reached 2 weeks later in Vales Sovereign (Figure 50). Irrigation regime had the same effect on ground cover development for both varieties. There was no significant difference in time to reach full ground cover between crops kept at Field Capacity or a 10 or 20 mm maximum SMD. Delaying irrigation until the SMD had increased to 30 mm slowed ground cover after about 4 weeks from emergence and full ground cover was reached c. 10 days later than the most advanced treatments. Delaying irrigation until a 40 mm SMD had been attained delayed full canopy cover by c. 20 days. Thereafter, all irrigated treatments maintained close to full ground cover until final harvest. Unirrigated crops, by contrast, only reached c. 85 % ground cover, and despite the rain in August, unirrigated Maris Piper crops began to senesce steadily from mid-August when the SMDs had exceeded 70 mm (see next section on SMDs).

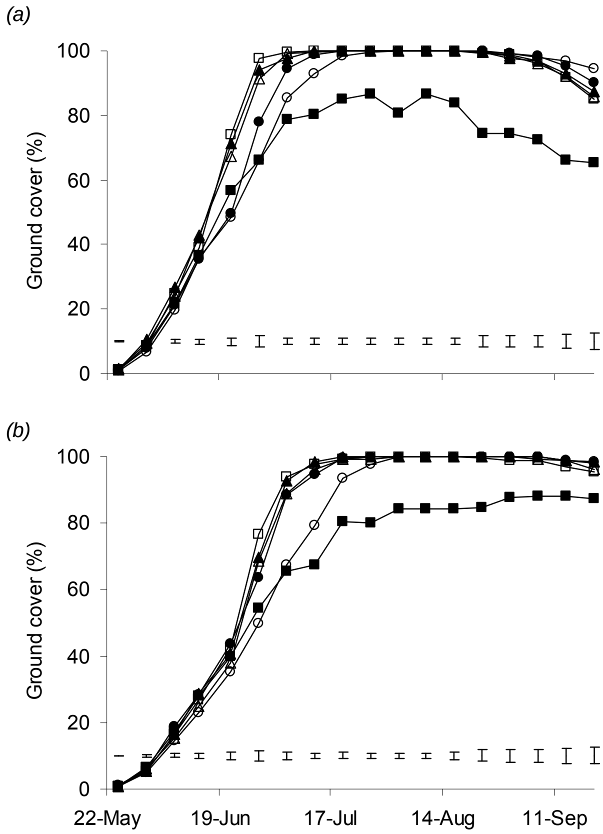

FIGURE 50. GROUND COVER (A) MARIS PIPER; (B) VALES SOVEREIGN IN EXPT 2010B. UNIRR, ■; 0, □; 10, ▲; 20, △; 30, ●; 40, ○.

4.6.3. Soil moisture deficits and water content

4.6.3.1. Modelled soil moisture deficits

The 2010 season was characterized by short periods of bright days throughout June and July, interspersed with longer spells of more average radiation but this still resulted in significantly higher evaporative demand for these two months than average. Combined with only 20 mm of rain from 10 June to 31 July, this meant that irrigation demand was high. August was dull with a low evaporative demand and there was heavy rain in late in the month. The maximum modelled SMD attained in unirrigated crops was 72-75 mm at the end of July. The scheduled treatments were maintained at or below their target SMD (Figure 51). Around the time of tuber initiation there was rainfall, but in the unirrigated, 30 and 40 mm SMD treatments the SMD increased beyond 15 mm SMD 7 days after initiation so the risk of infection by common scab would have increased. The 30 mm SMD treatment was not irrigated until the third week of the susceptible period for scab and the 40 mm treatment only in the last week.

4.6.3.2. Measured soil water content

Measurements of soil water content at 15 cm depth were taken every 10 minutes with Theta probes and data presented in Figure 52 show the hourly means with some missing periods due to logger failure. In general, the measurement showed that a differential in soil water content between irrigation treatments was maintained over most of the season in both varieties. In Maris Piper, the most frequently irrigated treatments (0, 10, 20 SMD) wetted up to Field Capacity and no wetter during the period prior the end of July (Figure 52a) but in Vales Sovereign the soils were wetter in than Field Capacity in the 0 SMD treatment during the 3 week period after tuber initiation (Figure 52b).

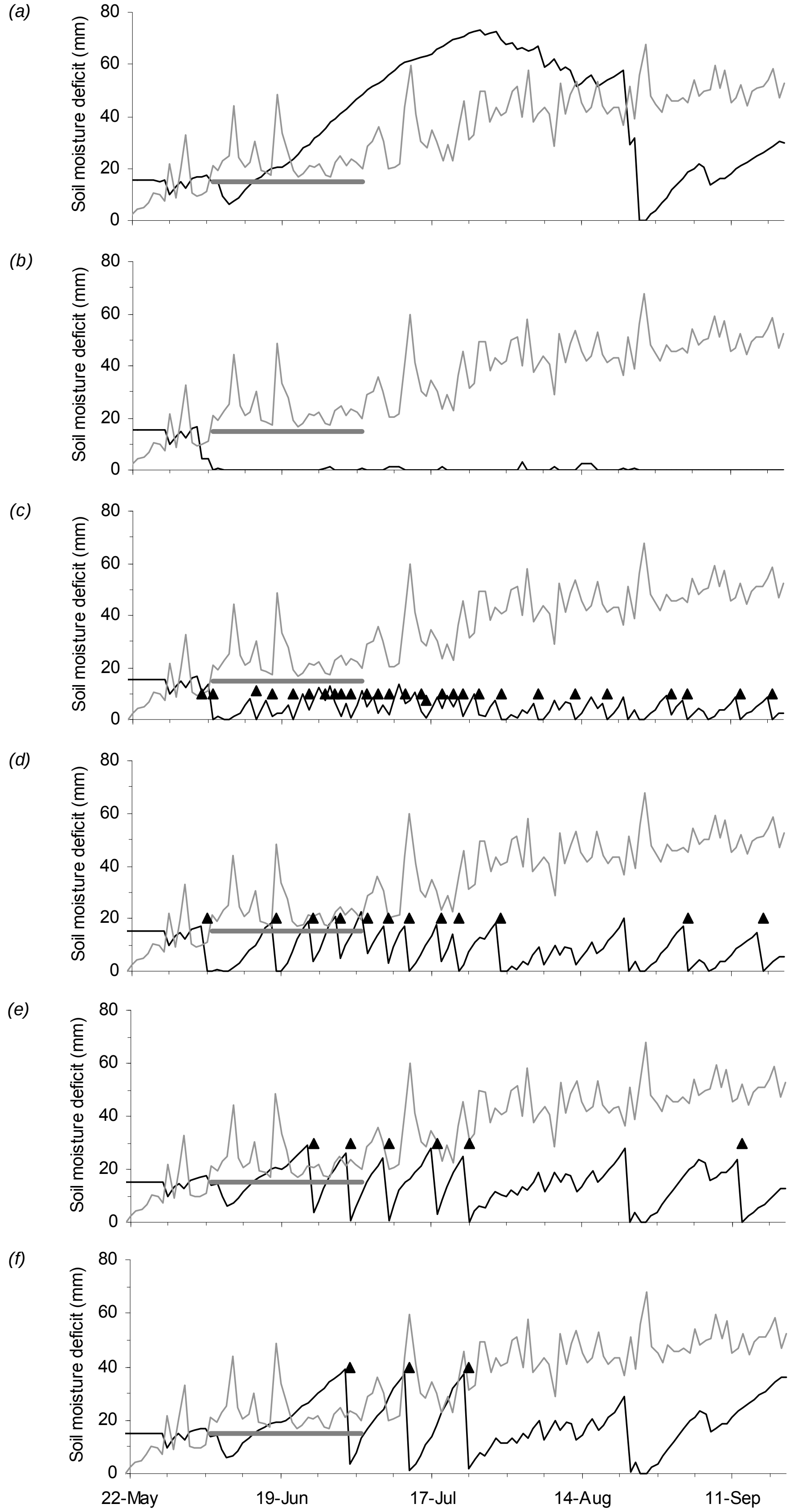

FIGURE 51. MODELLED SOIL MOISTURE DEFICITS IN EXPT 2010B. (A) UNIRR; (B) 0; (C) 10; (D) 20; (E) 30; (F) 40. MEAN OF BOTH VARIETIES. —— MODELLED; —— LIMITING. THICK SOLID LINE INDICATES SCAB CONTROL PERIOD. ▲ INDICATES IRRIGATION EVENTS (NOT SHOWN IN 0 FOR CLARITY).

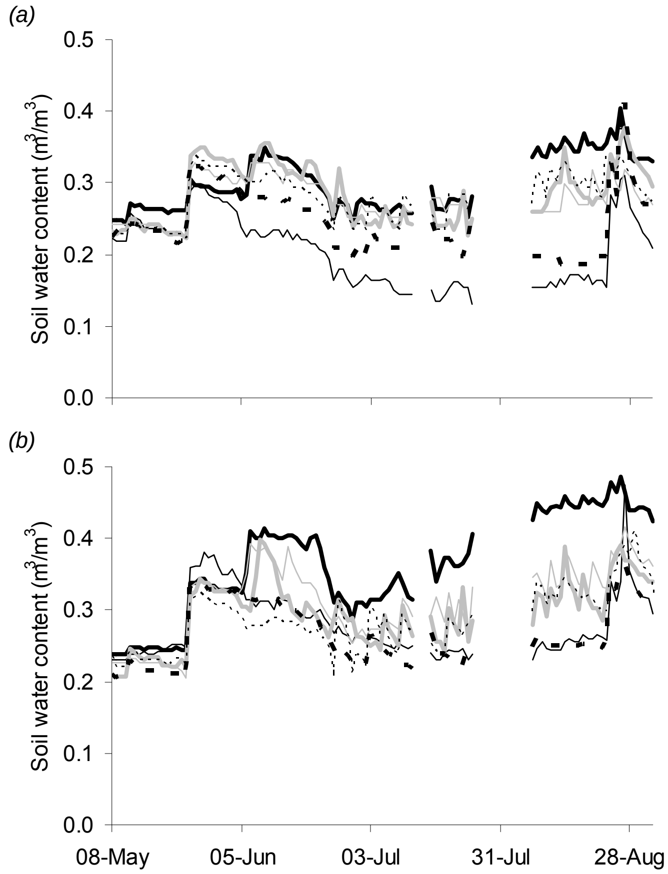

FIGURE 52. MEASURED SOIL WATER CONTENT AT 15 CM DEPTH (A) MARIS PIPER; (B) VALES SOVEREIGN IN EXPT 2010B. UNIRR —; 0 ▬; 10 —; 20 ▬; 30 ---; 40 _ _. MEAN HOURLY VALUES AND NEAN OF TWO REPLICATES ONLY

4.6.4. Number of tubers and tuber yield

The number of mainstems was similar for both varieties (Maris Piper 112 000/ha, Vales Sovereign 115 000 ± 3 100). Unlike the anomaly found in 2009, where early over-irrigation increased the number of tubers > 10 mm very dramatically compared with normal, scheduled irrigation, there was no effect on total number of tubers of maintaining the SMD at zero compared with either 10 or 20 mm SMD. However, irrigating at 30 or 40 mm SMD decreased the number of tubers compared with keeping the soil at Field Capacity but unirrigated crops had similar numbers of tubers to 0 SMD (Table 52). An earlier harvest taken 23 days after tuber initiation showed that there was no significant effect of irrigation regime on the total number of tubers initiated or the number > 10 mm.

The highest fresh and dry weight yields were obtained by maintaining the soil at Field Capacity but the difference in yield was not significant between 0 and 10 mm SMD (Table 52). There was a smaller decrease in fresh and dry weight yields in Vales Sovereign as the SMD increased from 0 to 30 mm than in Maris Piper. Unirrigated Maris Piper had a lower fresh weight yield than Vales Sovereign but a similar dry matter yield.

Variety	Irrigation regime	No. of tubers (000/ha)	Total fresh weight yield (t/ha)	Fresh weight yield > 40 mm (t/ha)	Tuber dry matter yield (t/ha)
Maris Piper	Unirr	452	45.0	40.5	10.9
	0	497	72.9	70.0	18.8
	10	462	63.1	60.0	16.5
	20	487	63.7	60.8	16.1
	30	404	59.4	56.9	15.4
	40	423	60.2	57.2	15.7
Vales Sovereign	Unirr	402	53.9	49.4	11.6
	0	423	73.3	71.0	16.0
	10	404	69.5	67.3	15.6
	20	372	66.6	64.8	15.0
	30	384	66.9	65.4	15.2
	40	369	59.9	57.6	12.3
S.E. (21 D.F.)		23.3	3.61	3.87	0.88

TABLE 52. NUMBER OF TUBERS AND TUBER YIELDS AT FINAL HARVEST IN EXPT 2010B

4.6.5. Tuber dry matter concentration

Vales Sovereign had a lower tuber dry matter concentration than Maris Piper. Despite considerable differences in water supply during the course of the season, there were no significant differences in dry matter concentration that remained at final harvest (Figure 53). Three weeks after tuber initiation, treatments kept at Field Capacity had lower dry matter concentration than those kept at 20 mm SMD, which in turn were lower than Unirrigated and 40 mm treatments. Two weeks subsequent to this, unirrigated treatments had greater dry matter concentration than all irrigated treatments but any effect of irrigation regime had disappeared by 18 August following a dull, wet early part of the month.

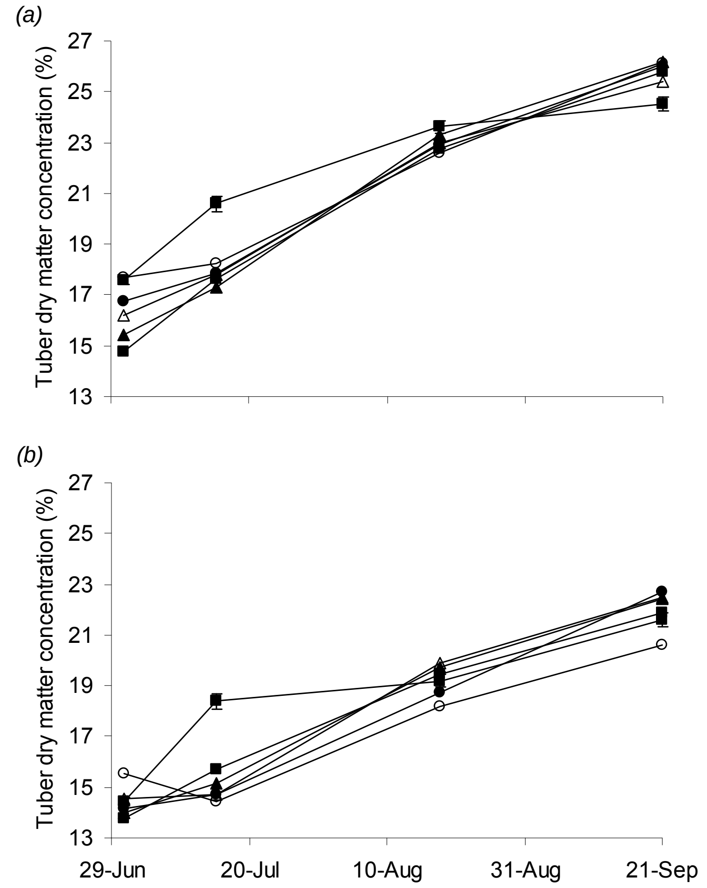

FIGURE 53. TUBER DRY MATTER CONCENTRATION ([DM]) IN (A) MARIS PIPER; (B) VALES SOVEREIGN IN EXPT 2010B. UNIRR, ■; 0, □; 10, ▲; 20, △; 30, ●; 40, ○.

4.6.6. Common scab

In Maris Piper, virtually every tuber had some common scab (99.4 % incidence), whereas in Vales Sovereign, there were c. 5 % of tubers completely free from scab. Tubers with > 5 % SA are generally regarded as unsuitable for packing and a typical minimum acceptable packout is 70 %, i.e. ≤ 30 % rejectable tubers. The incidence of tubers with < 5 % SA infected was on average much lower in Maris Piper (44.3 %) than Vales Sovereign (97.5 %). In Maris Piper, the proportion of tubers with < 5 % SA infected with scab decreased with increasing soil dryness. However, the best packout was only 68 % in soils kept at 0 mm SMD, decreasing to only 51 % in crops maintained below 20 mm SMD throughout (Table 53). Where soils were maintained at 40 mm SMD, only 21-29 % of the crop was suitable for packing. In contrast, 97-100 % of irrigated Vales Sovereign tubers would be acceptable for packing based on common scab severity, even when only irrigated once at 3 weeks after tuber initiation (40 mm SMD treatment).

The overall severity of scab in unirrigated Maris Piper (28.1 % SA) was greater than unirrigated treatments in recent experiments at CUF during (19.7-20.9 %) and the wettest plots had around twice as severe scab as in previous seasons (11.7 % SA compared with in 6.8 % in 2009, 4.5 % in 2008 and 6.4 % in 2007, respectively). There was a gradual reduction in severity of scab in Maris Piper as the frequency of irrigation decreased (Table 53). There was no significant effect of irrigation regime on scab severity in Vales Sovereign.

Variety	Irrigation regime	Incidence < 5 % surface area		Severity
		%	Ang. trans.	% SA affected
Maris Piper	Unirr	28.9	32.2	28.1
	0	68.4	56.3	11.7
	10	60.9	51.3	14.2
	20	50.8	45.5	16.7
	30	35.5	36.3	25.1
	40	21.2	26.6	30.2
Vales Sovereign	Unirr	91.2	73.9	4.1
	0	97.2	82.3	4.1
	10	98.4	85.8	3.4
	20	100.0	90.0	3.2
	30	99.1	86.8	3.2
	40	99.0	86.6	2.1
S.E. (21 D.F.)		-	3.78	2.93

TABLE 53. COMMON SCAB INCIDENCE AND SEVERITY IN EXPT 2010B

4.6.7. Tuber cracking

In all irrigation treatments, some tubers had external growth cracks. Vales Sovereign had the greatest incidence of cracking but the cracks were mostly of a different form to those observed on Maris Piper tubers. Cracking in Maris Piper was mostly single, deep cracks, whereas in Vales Sovereign, the cracks were mostly superficial. In Maris Piper, keeping the soil at Field Capacity increased the incidence of deep cracks compared with all other irrigation treatments but the incidence was only half of that observed in Expt 2009b when the soils were maintained wetter than Field Capacity for the 3-week period after tuber initiation. Cracking centred on lenticels was also increased in Maris Piper where soils were kept at Field Capacity. Vales Sovereign had a much higher incidence of cracking than Maris Piper since many tubers had some superficial cracking (Table 54). Reducing the amount of water applied to this variety decreased the incidence of superficial cracking, most notably from maintaining an SMD of 0 mm versus an SMD of 10 mm. Keeping the soil at Field Capacity throughout the season resulted in > 30 % of tubers having an unacceptable level (> 5 % SA) of superficial cracking. Withholding irrigation completely in Vales Sovereign reduced the incidence of superficial cracking to the values measured in most Maris Piper treatments.

Variety	Irrigation regime	Total cracks Incidence (%)	Ang. trans.†	Deep cracks Incidence (%)	Ang. trans.	Superficial cracks Incidence (%)	Ang. trans.	Incidence < 5 % SA affected
Maris Piper	Unirr	4.7	12.2	1.3	6.4	3.4	10.1	98.9
	0	18.2	25.0	6.7	14.8	11.5	19.6	97.9
	10	7.2	15.4	0.8	4.2	6.4	14.6	99.6
	20	5.0	11.0	0.9	3.1	4.2	10.2	98.7
	30	6.4	14.3	1.1	4.8	5.3	12.6	99.5
	40	7.2	14.4	2.2	5.0	5.0	12.3	98.7
Vales Sovereign	Unirr	6.3	11.6	0.8	3.0	5.4	10.9	100.0
	0	62.2	52.1	0.9	4.4	61.3	51.5	68.6
	10	36.8	37.0	0.0	0.0	36.8	37.0	91.0
	20	35.0	35.6	0.0	0.0	35.0	35.6	89.1
	30	28.5	32.2	0.0	0.0	28.5	32.2	95.4
	40	22.7	28.1	2.6	9.2	20.1	26.2	98.5
S.E. (21 D.F.)		-	4.24	-	2.31	-	4.01	-

†Angularly transformed data for statistical analysis

TABLE 54. TUBER CRACKING INCIDENCE AND SEVERITY IN EXPT 2010B

4.7. Experiment 2010c

4.7.1. Emergence and ground cover

Russet Norkotah emerged sooner after planting (20 May) than Alturas (22 May) or Umatilla Russet (23 May). Temperatures were colder than average in June and ground cover was slower to develop than normal. Irrigation regime had no effect on ground cover development until mid-June. Thereafter, maintaining soil close to Field Capacity (< 6 mm SMD) slightly increased the early rate of ground cover development compared with allowing the SMD to reach 20 mm. By the commencement of the measurement period (21 June), ground covers were c. 91-93 % in Alturas and Umatilla Russet and c. 81 % in Russet Norkotah. On average, WSU treatments had slightly more ground cover (91.8 %) on 21 June than the CUF and Drought treatments (87.5 ± 1.08 %).

Ground covers were measured prior to each reading of leaf water potential, i.e. three-four times daily during the measurement period. Canopy cover was still increasing during this period. Ground cover of Drought treatments decreased owing to wilting during the afternoon, with wilting being most obvious in Russet Norkotah and Umatilla Russet which had not reached complete cover (Figure 54). On the two hottest days (23 and 24 June), Drought plots had c. 7 % less ground cover by late afternoon in these two varieties, whereas in Alturas the difference was closer to 3 %. CUF irrigation treatments showed only a few signs of wilting, whilst WSU treatments did not wilt, except slightly in Russet Norkatah on 22 June (Figure 54b).

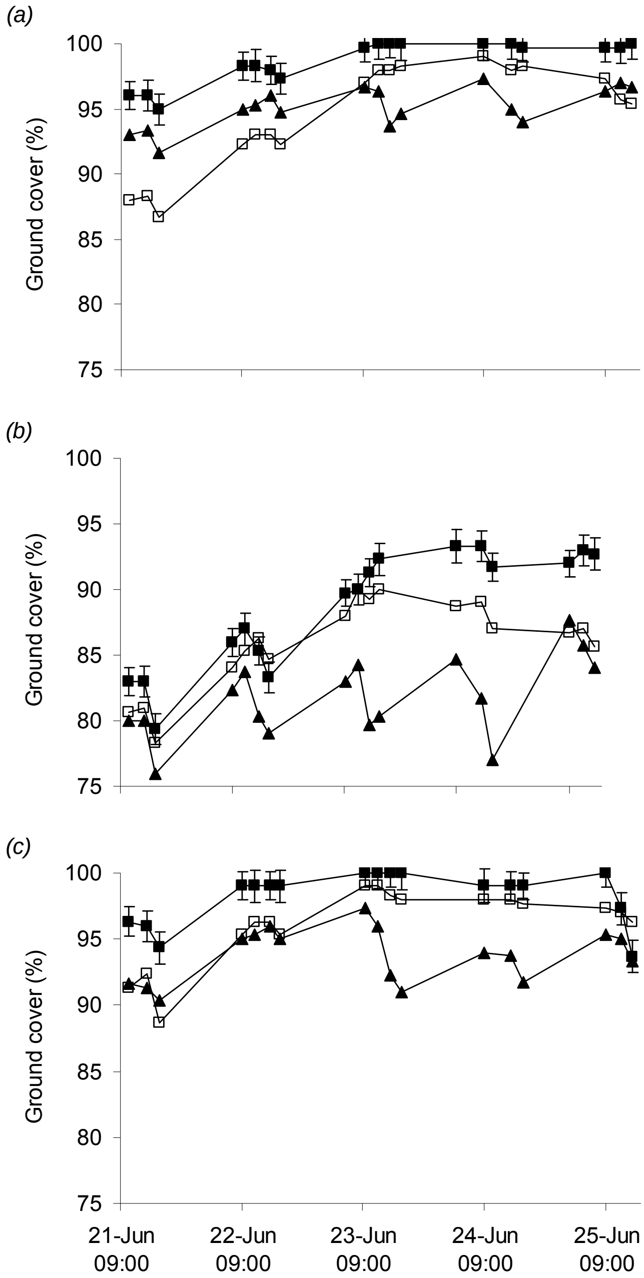

FIGURE 54. CHANGES IN GROUND COVER DURING EACH DAY OF THE MEASUREMENT PERIOD IN EXPT 2010C. *(A)* ALTURAS; *(B)* RUSSET NORKOTAH; *(C)* UMATILLA RUSSET. WSU, ■; CUF, □; DROUGHT, ▲. S.E. BARS BASED ON 12 D.F.

Measurements of ground cover were taken only infrequently during senescence but Alturas still had c. 85 % ground cover at defoliation, whilst Russet Norkotah started senescing in mid-August and was completely dead 1 week before defoliation. Umatilla Russet started senescing at the beginning of September and still had c. 65 % ground cover at defoliation.

4.7.2. Soil moisture deficits and water use

The 4 weeks after emergence were cooler than average with several significant rainfall events that reduced the need for irrigation. Temperatures were higher in the measurement period than the preceding or succeeding week but the evaporative demand was still lower than average for the time of year. Soil moisture deficits were maintained close to the target from late June until the end of July when the soils were allowed to progressively dry out prior to defoliation. The data for Alturas are shown in Figure 55. The limiting SMD during this period was c. 20 mm and the CUF and Drought treatments reached or exceeded this in late July so that water use slowed. Daily water use was considerably reduced during August in CUF and Drought treatments and even WSU treatment came under water stress in mid-late August when the evaporative demand was > 6 mm/day.

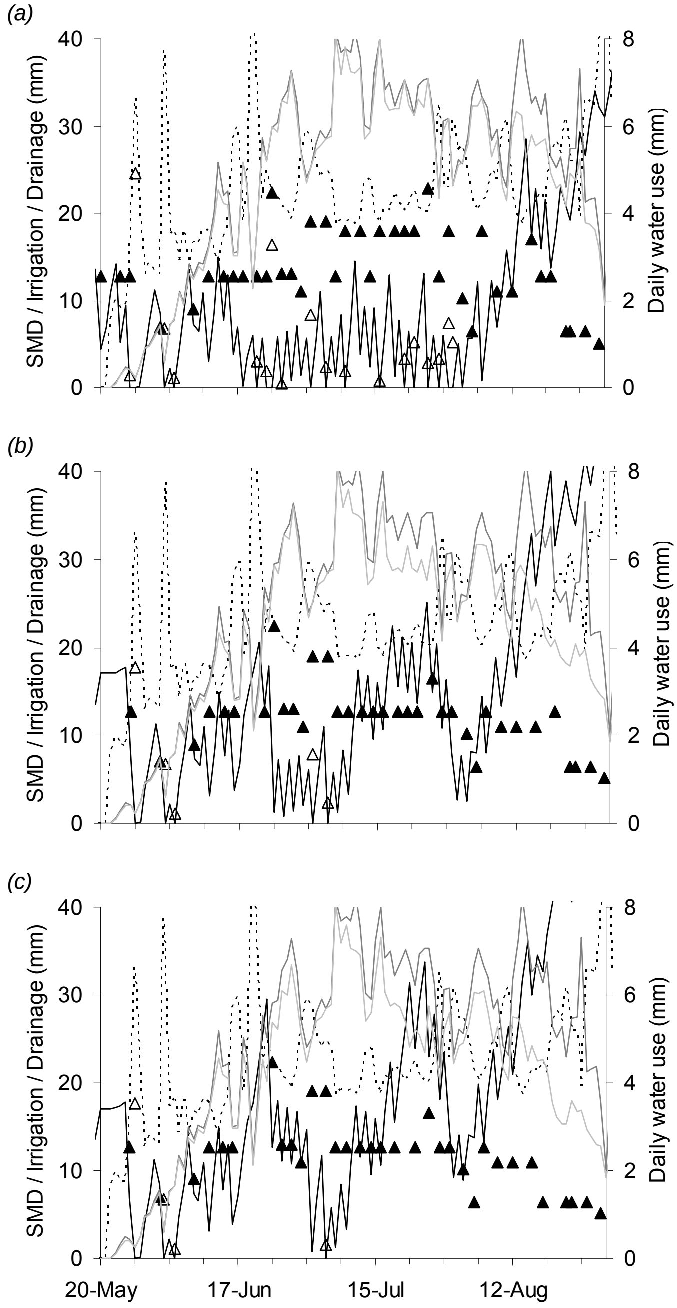

FIGURE 55. SOIL MOISTURE DEFICITS (SMD) AND DAILY WATER USE IN ALTURAS IN EXPT 2010C. SMD, ▬; LIMITING SMD,---- ; IRRIGATION ▲; DRAINAGE, △; POTENTIAL WATER USE, ▬; MODELLED WATER USE, ▬.

Using the CUF model developed under UK conditions, the water use for the measurement period was calculated. It showed that even though the temperature and evaporative demand were only moderate for Washington (comparable with very high for the UK) and the soil had a large easily-available water holding capacity, water use would be c. 10-12 % lower where the SMD was maintained at 20 mm than where the SMD was < 10 mm and c. 22 % lower where the SMD was 30 mm (Table 55). Over the course of the season, managing the irrigation at 10-20 mm SMD (CUF) would result in a reduction in water use by the crop of c. 30 mm compared with the WSU treatment which was generally maintained at < 10 mm SMD (Table 55). However, owing to the paucity of ground cover data during August, care is needed in interpreting difference in entire-season SMDs.

	21-25 June			Season		
Variety	WSU	CUF	Drought	WSU	CUF	Drought
Alturas	26.2	24.2	22.4	514	476	458
Russet Norkotah	23.6	21.9	19.9	439	418	405
Umatilla Russet	26.2	24.5	22.2	506	474	499

TABLE 55. EFFECT OF IRRIGATION REGIME ON MODELLED WATER USE (MM) DURING 21-25 JUNE AND THE ENTIRE SEASON IN EXPT 2010C

4.7.3. Stomatal resistance

Frequent measurements showed that stomatal resistance increased considerably during hot days in the Drought treatments and to a lesser extent in the CUF treatments (Figure 56). There was little diurnal fluctuation in the wet WSU plots. The greatest changes from morning to late afternoon were observed in Russet Norkotah, with Umatilla Russet intermediate and Alturas increasing the least. Following irrigation of Drought plots with 22 mm in late afternoon of 24 June which reduced the SMD to 12-13 mm, the increase in resistance on 25 June was smaller than on previous days but still significantly greater than WSU or CUF treatments.

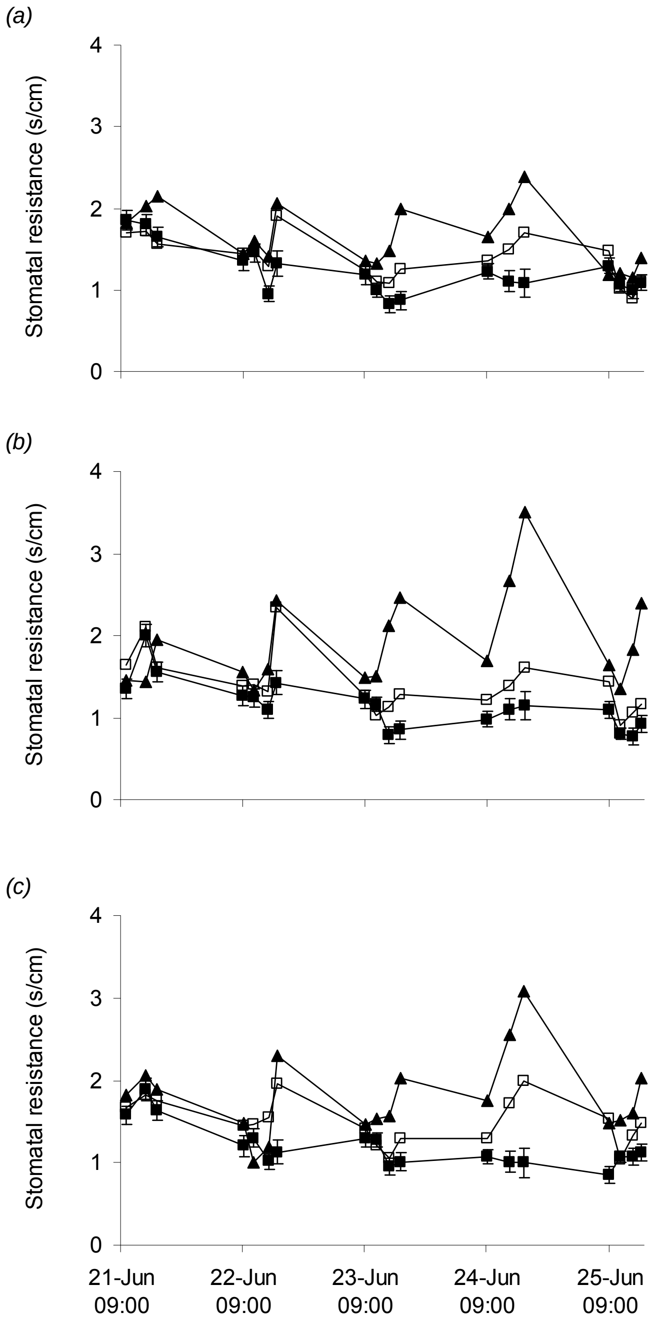

FIGURE 56. STOMATAL RESISTANCE DURING PERIOD 21-25 JUNE IN EXPT 2010C. *(A)* ALTURAS; *(B)* RUSSET NORKOTAH; *(C)* UMATILLA RUSSET. WSU, ■; CUF, □; DROUGHT, ▲. S.E. BARS BASED ON 12 D.F.

4.7.4. Leaf water potential

Leaf water potentials generally commenced each day at similar values irrespective of irrigation treatment and the day of the week in Alturas and Umatilla Russet but the morning water potential readings in Russet Norkotah equilibrated to different values each day (Figure 57).

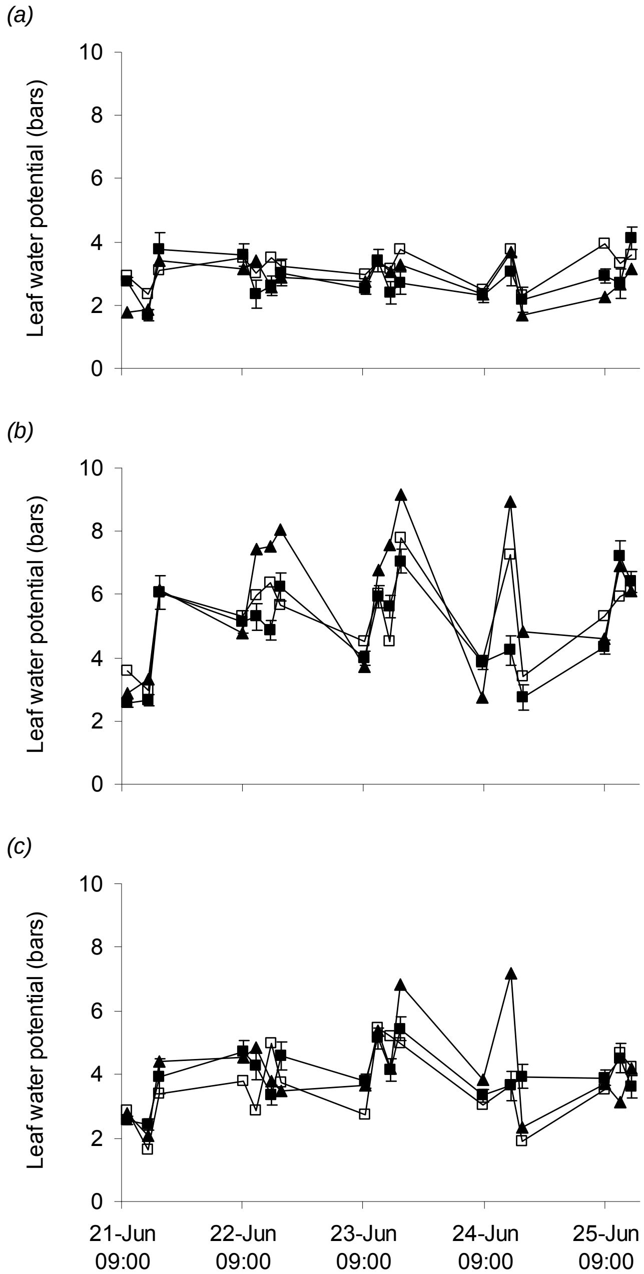

FIGURE 57. LEAF WATER POTENTIAL DURING PERIOD 21-25 JUNE IN EXPT 2010C. *(A)* ALTURAS; *(B)* RUSSET NORKOTAH; *(C)* UMATILLA RUSSET. WSU, ■; CUF, □; DROUGHT, ▲. S.E. BARS BASED ON 12 D.F.

There were only small (largely non-significant) differences in water potential between irrigation treatments in Alturas (Figure 57a), while the differences were greater (and largely significant) between irrigation regimes in Russet Norkotah and Umatilla Russet. In Russet Norkotah, water potential increased throughout the day and then recovered overnight, with the changes being greatest in Drought, intermediate in CUF treatments and smallest in WSU (Figure 57b). In Umatilla Russet, there was no significant difference between WSU and CUF treatments in the changes in water potential during the day but water potential in Drought treatments increased more during the day on 23 and 24 June (Figure 57c).

There were significant, positive relationships between the daily peak stomatal resistance and the modelled SMD at the beginning of the day, with the slope being greatest for Russet Norkotah and least for Alturas (Figure 58a). There were also significant positive relationships between leaf water potential and SMD in Russet Norkotah and Umatilla Russet but allowing the SMD to increase to close to 30 mm in Alturas had no effect on the maximum leaf water potential measured during the following day (Figure 58b).

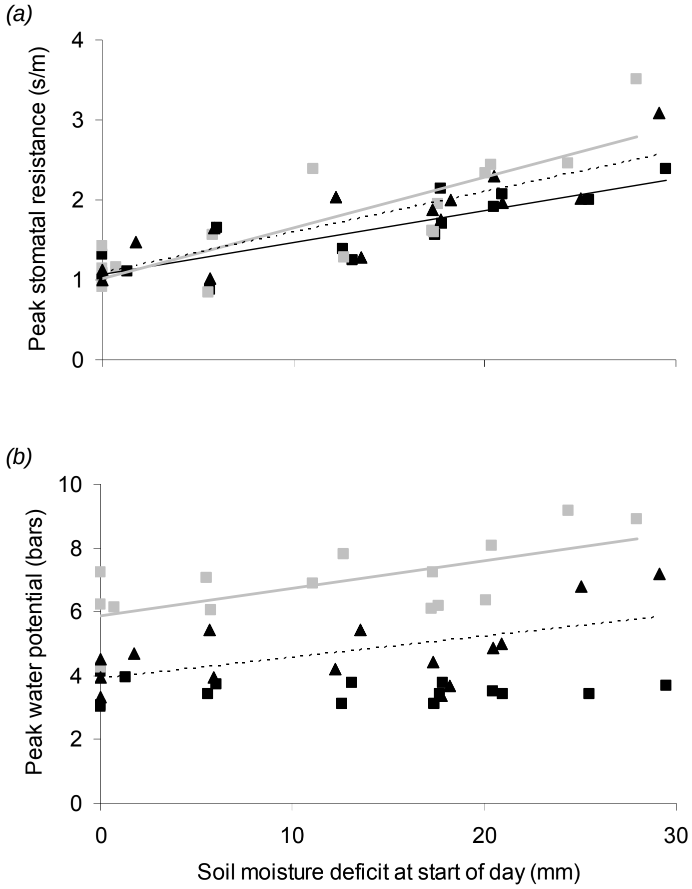

FIGURE 58. RELATIONSHIP BETWEEN DAILY (A) PEAK STOMATAL RESISTANCE (SR) AND (B) PEAK LEAF WATER POTENTIAL (WP) AND SOIL MOISTURE DEFICIT (SMD) AT THE START OF THE MEASUREMENT DAY IN EXPT 2010C. ALTURAS, —■—; RUSSET NORKOTAH, —■—; UMATILLA RUSSET, ---▲---. SIGNIFICANT RELATIONSHIPS: (A) ALTURAS, SR = 0.0402 (±0.00647)*SMD+1.06 (±0.102), R2 = 0.75; RUSSET NORKOTAH, SR = 0.0634 (±0.0119)*SMD+1.0 (±0.180), R2 = 0.69; UMATILLA RUSSET, SR = 0.0506 (±0.00810)*SMD+1.08 (±0.127), R2 = 0.75; (B) RUSSET NORKOTAH, WP = 0.0856 (±0.0277)*SMD+5.88 (±0.420), R2 = 0.42; UMATILLA RUSSET, WP = 0.0658 (±0.0267)*SMD+3.90 (±0.417), R2 = 0.32.

Maintenance of an open stomatal aperture i.e. low resistance, is an important component of maximising gaseous exchange rate and therefore photosynthetic rate. Additionally, as water potential increases, tissue loses strength and leaves begin to wilt, reducing light absorption by the canopy. The period studied was only moderately hot for Washington (maximum temperature on 22-25 June was 27-29 °C) where there were 26 days over 30 °C and 3 days over 35 °C in 2010. Increasing the temperature, and therefore the evaporative demand, would probably increase the slopes of the relationships between leaf water potential or stomatal resistance and SMD.

4.7.5. Tuber yield and dry matter concentration

Despite the lack of any significant difference in total or US #1 and #2 yield (total yield minus greens and other culls), there was a consistent effect across all varieties of the WSU irrigation treatment having a higher yield than CUF or Drought treatments. Tuber yields were larger in Alturas than in the other two varieties (Table 56) and this yield difference was largely a consequence of longer-lived canopies and high tuber dry matter yields rather than variations in tuber dry matter concentration as the dry matter % was much higher in Alturas than the fresh-market Russet Norkotah (Table 57).

	Variety		
Irrigation regime	**Alturas**	**Russet Norkotah**	**Umatilla Russet**
WSU	110.8	78.4	81.9
CUF	103.0	68.8	69.9
Drought	96.0	64.6	72.0
S.E. (12 D.F.)	6.58		
S.E. (same irrigation)	3.93		

TABLE 56. TOTAL TUBER YIELD (T/HA) IN EXPT 2010C

	Variety		
Irrigation regime	**Alturas**	**Russet Norkotah**	**Umatilla Russet**
WSU	21.1	18.4	21.2
CUF	20.2	18.2	21.1
Drought	20.8	17.1	21.4
S.E. (12 D.F.)	0.41		
S.E. (same irrigation)	0.39		

TABLE 57. TUBER DRY MATTER CONCENTRATION (%)IN EXPT 2010C

4.8. Commercial fields 2009

4.8.1. Texture and organic matter percentage

Textural analysis of three composite soil samples in each field showed that there was a range in clay contents from 9 to 35 % and clay + silt from 19 to 83 %, whilst organic matter percentage ranged from to 0.9 to 3.5 % (Table 58).

Field	Soil Association†	Texture‡	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)
Medlers Quebec	Newport 3	LS	81	10	9	1.8
Bawsdeswell 26	Burlingham 1	LS	80	11	9	1.2
Ludham R7	Wick 2	SL	56	30	14	2.0
Overton Sewage	Wick 3	SL	54	32	14	1.7
PF5	Wick 2	SZL	49	34	17	1.3
Harrolds 1	Barrow	SL	64	20	16	1.2
Harrolds 2	Barrow	SL	72	16	12	1.0
Papworth 904	Wick 2	SL	54	34	12	3.5
HBS NE5	Gresham	SL	52	34	14	1.3
Overton Tooke	Wick 3	SL	54	30	16	1.1
Crane 15	Wick 2	SL	57	28	15	1.3
Spearhead Washpit	Worlington	SL	79	11	10	1.2
Spearhead S. Common	Burlingham 3	SL	77	12	11	1.2
Papworth 22	Wick 2	SZL	42	41	17	1.6
Papworth 728	Wick 2	SL	55	31	14	1.8
Sutton 164	Gresham	SZL	41	42	17	2.1
QV Oaks	Swaffham Prior/Isleham	CL	40	34	26	3.3
Garrods Normans	Burlingham 1	SL	72	17	11	0.9
Stevenson Wood	Stretham	CL	23	44	33	2.8
Stevenson Brackleys	Stretham	ZCL	17	50	33	3.0
Stevenson Blacklands	Stretham	CL	20	45	35	3.2
Mean			54	29	37	1.8

†Soil Survey of England and Wales (1983)
‡S = sand, C = clay, Z = silt, L = Loam(y)

TABLE 58. SOIL ASSOCIATION, TEXTURAL CLASSIFICATION, CLAY, SILT AND ORGANIC MATTER PERCENTAGES BASED ON AN AVERAGESAMPLE OF ALL 12 LOCATIONS IN EACH FIELD IN 2009

4.8.2. Bulk density

4.8.2.1. Density at cultivation depth

Table 59 shows the bulk densities at 25-30 and 30-35 cm. There was, on average, a greater bulk density at 30-35 cm depth than at 25-30 cm, though there was no difference in density over the cultivation depth at Crane 15, Spearhead Washpit, Spearhead S. Common and Stevenson Brackleys. The greatest bulk densities were on the soils with a high percentage of fine sand and the lowest on clay-textured soils and within a textural class were close to the optimum for water-holding capacity (Archer & Smith 1972).

4.8.2.2. Ridge density

Bulk density within the ridge ranged from c. 0.9 g/cm3 on clay soils planted in ridges to 1.3 g/cm3 on fine sandy loam soils where the crops were grown in beds (e.g. PF5, Papworth 728, Table 59).

Field	Ridge density (g/cm3)	Density 25-30 cm (g/cm3)	Density 30-35 cm (g/cm3)	Mean density 25-30 cm (g/cm3)
Medlers Quebec	1.22	1.17	1.35	1.26
Bawsdeswell 26	1.12	1.47	1.56	1.52
Ludham R7	1.09	1.30	1.45	1.37
Overton Sewage	1.09	1.20	1.37	1.29
PF5	1.32	1.47	1.51	1.49
Harrolds 1	1.07	1.50	1.59	1.55
Harrolds 2	1.24	1.43	1.48	1.46
Papworth 904	0.93	1.10	1.24	1.17
HBS NE5	1.11	1.45	1.47	1.46
Overton Tooke	1.15	1.29	1.38	1.33
Crane 15	1.25	1.52	1.50	1.51
Spearhead Washpit	1.29	1.42	1.40	1.41
Spearhead S. Common	1.23	1.35	1.33	1.34
Papworth 22	1.04	1.22	1.33	1.27
Papworth 728	1.27	1.27	1.44	1.35
Sutton 164	1.08	1.22	1.42	1.32
QV Oaks	1.13	1.25	1.41	1.33
Garrods Normans	1.27	1.41	1.48	1.44
Stevenson Wood	0.97	1.25	1.30	1.28
Stevenson Brackleys	0.92	1.32	1.28	1.30
Stevenson Blacklands	0.88	1.22	1.28	1.25
Mean	1.13	1.33	1.41	1.37
S.E. (20 D.F.)	0.130	0.121	0.096	0.104

TABLE 59. RIDGE DENSITY AND BULK DENSITY AT 25-30 AND 30-35 CM DEPTHS IN 2009

4.8.3. Relationship between bulk density and soil water content at cultivation

In 20 out of the 21 fields sampled, there was a significant positive correlation between the mean soil bulk density at 25-35 cm depth and the water content at cultivation but the magnitudes and relative changes in bulk density differed between fields. In fields where there was limited variation in soil texture across the sampling area, the relationships were relatively close (e.g. Figure 59g and Figure 60b) but the field with the greatest variation in clay content, QV Oaks (Figure 59j), had the greatest correlation between bulk density and soil water content. Clearly, the wetter soil a soil was at cultivation, the greater the compaction measured at cultivation depth. Combining the data from two similar soils (same Soil Association with respect to clay and silt proportion) produced a unifying relationship albeit with very different soils water contents prior to planting for the two fields (Figure 61). The overall effects of texture and organic matter on the slope of the relationship between soil water content and bulk density are reported in the results presented for 2010 (p. 142).

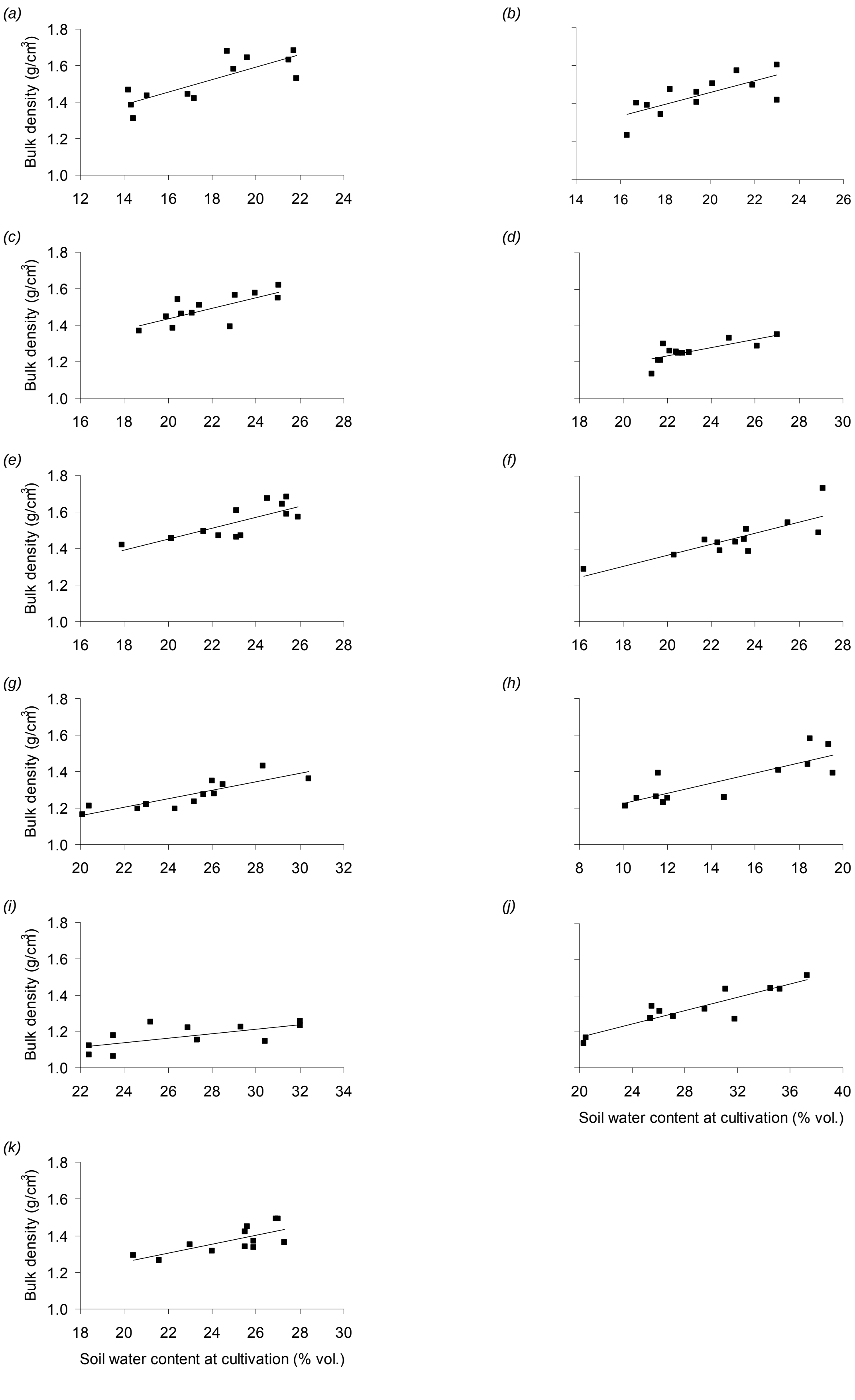

FIGURE 59. EFFECT OF SOIL WATER CONTENT AT CULTIVATION ON BULK DENSITY AT 25-35 CM DEPTH IN 2009. *(A)* BAWDESW. 26; *(B)* GARRODS NORMANS; *(C)* PF5; *(D)* MEDLERS QUEBEC; *(E)* HARROLDS 1; *(F)* HARROLDS 2; *(G)* PAPWORTH 22; *(H)* PAPWORTH 728; *(I)* PAPWORTH 904; *(J)* QV OAKS; *(K)* LUDHAM R7.

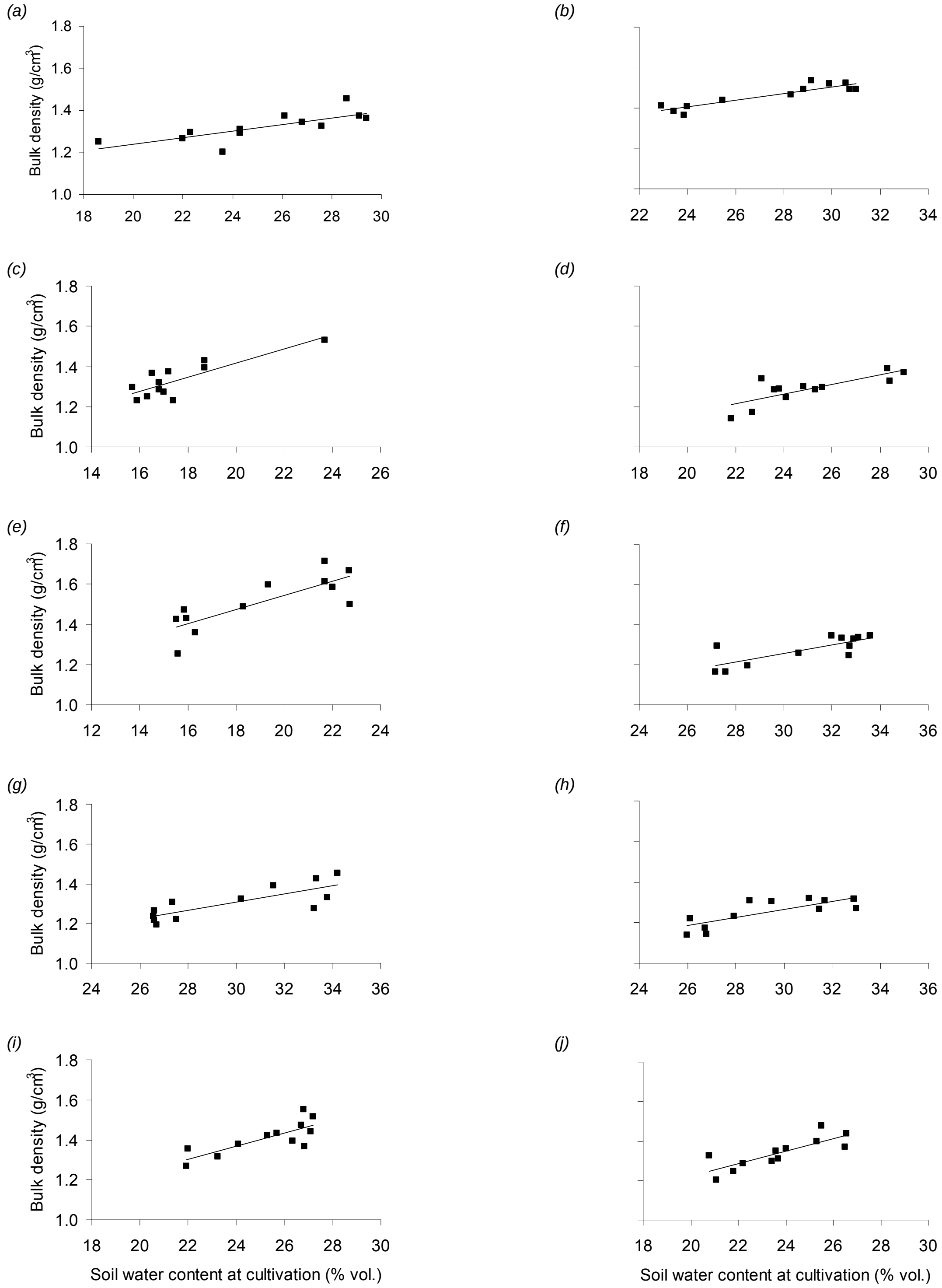

FIGURE 60. EFFECT OF SOIL WATER CONTENT AT CULTIVATION ON BULK DENSITY AT 25-35 CM DEPTH IN 2009. (A) SUTTON 164; (B) HBS NE5; (C) OVERTON TOOKE; (D) OVERTON SEWAGE; (E) CRANE 15; (F) STEVENSON WOOD; (G) STEVENSON BRACKLEYS; (H) STEVENSON BLACKLANDS; (I) SPEARHEAD WASHPIT; (J) SPEARHEAD S. COMMON.

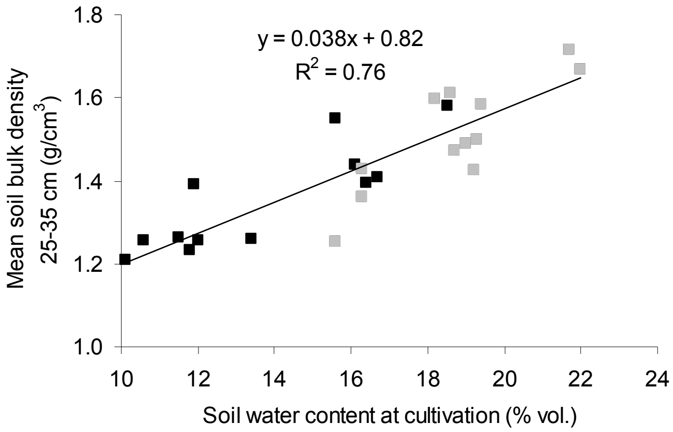

FIGURE 61. EFFECT OF SOIL WATER CONTENT AT CULTIVATION ON BULK DENSITY AT 25-35 CM DEPTH ON TWO SIMILAR SOILS IN 2009. PAPWORTH 728 (■); CRANE 15 (■).

Field	Slope	S.E.	Fprob	Intercept	S.E.	VAR	Range in water content (%) Min	Max
Bawsdeswell 26	0.0338	0.00795	0.002	0.91	0.144	60.8	14.2	21.9
Garrods Normans	0.0316	0.00928	0.007	0.83	0.182	49.1	16.3	23.0
PF5	0.0291	0.00563	0.007	0.85	0.189	48.6	18.7	25.0
Medlers Quebec	0.0338	0.00625	0.004	0.73	0.145	53.3	21.3	27.0
Harrolds 1	0.0299	0.00771	0.003	0.85	0.179	56.1	17.9	25.9
Harrolds 2	0.0300	0.00695	0.002	0.76	0.161	61.6	16.2	27.1
Papworth 22	0.0234	0.00439	<0.001	0.69	0.110	71.4	20.1	30.4
Papworth 728	0.0283	0.00602	<0.001	0.94	0.090	65.7	10.1	19.5
Papworth 904	0.0123	0.00455	NS	0.84	0.123	26.3	22.4	32.0
QV Oaks	0.0185	0.00279	<0.001	0.80	0.082	79.6	20.3	37.3
Ludham R7	0.0248	0.00731	0.011	0.76	0.183	48.8	20.4	27.3
Sutton 164	0.0154	0.00423	0.004	0.93	0.107	52.8	18.6	29.4
HBS NE5	0.0168	0.00261	<0.001	1.00	0.072	78.7	22.9	31.0
Overton Tooke	0.0349	0.00751	<0.001	0.72	0.133	65.2	15.7	23.7
Overton Sewage	0.0239	0.00618	0.003	0.69	0.155	55.8	21.8	29.0
Crane 15	0.0354	0.00836	0.002	0.84	0.161	60.6	15.5	22.7
Stevenson Wood	0.0210	0.00539	0.003	0.63	0.167	56.3	27.2	33.6
Stevenson Brackleys	0.0209	0.00458	0.002	0.68	0.146	61.1	26.6	34.2
Stevenson Blacklands	0.0205	0.00509	0.002	0.65	0.150	58.1	26.0	33.0
Spearhead Washpit	0.0325	0.00780	0.002	0.59	0.198	59.8	21.9	27.2
Spearhead S Common	0.0325	0.00712	0.001	0.57	0.169	64.4	20.8	26.6
Mean	0.0262			0.77		58.8	19.8	27.9
S.E. (20 D.F.)	0.00702			0.119				
						11.34	4.24	4.55

TABLE 60. SUMMARY 2009: SLOPE OF BULK DENSITY VS SOIL WATER CONTENT RELATIONSHIP (G/CM^3/%), SIGNIFICANCE OF RELATIONSHIP (FPROB), INTERCEPT OF RELATIONSHIP, PERCENTAGE VARIANCE ACCOUNTED FOR (VAR) AND RANGE IN SOIL WATER CONTENT AT CULTIVATION. S.E. BASED ON 10 D.F.

4.8.4. Soil resistance

Stalham et al. (2007) showed that for soils at Field Capacity, a resistance of 1 MPa slowed the potential rate of root growth by half, 2 MPa down to one quarter and 3 MPa prevented root elongation completely. Resistances over 3 MPa within cultivation depth should therefore be tackled as a priority as they will restrict rooting considerably if shallow. At resistances > 2 MPa, cultivation to remove the areas of compaction would be beneficial for root growth.

Owing to the time constraints of visiting every site as close after planting as possible to measure resistance so that differences in soil water content did not confound measurements of soil strength, only 14 fields could be assessed. Only two fields had moderate soil resistance (< 2 MPa) throughout the top 50 cm (Overton Tooke, Spearhead Washpit, Figure 62c, d). Harrolds 1 had a marked pan between 25 and 30 cm depth but the pan was 5 cm deeper in Harrolds 2 (Figure 62a). At destoning depth (30-35 cm from top of the ridge), Bawdeswell 26 and Harrolds 2 had soil strengths > 2 MPa which would provide a severe impediment to root growth (Figure 62a). Several fields had resistances > 3 MPa in the top 60 cm of the profile (Bawdeswell 26, Harrolds 1, Harrolds 2, Papworth 904, HBS NE5, Overton Sewage and Crane 15) which would prevent deeper root penetration (Figure 62a, b, c).

Figure 63 shows the relationship between soil resistance and bulk density in three of the sampled fields. There was a directional and magnitudinal correlation both between the changes in soil resistance and bulk density between 25 cm and 35 cm within the cultivation zone and between soil resistance and bulk density across all three fields but the absolute values of bulk density at the same soil resistance differed between fields.

4.8.5. Ped size distribution

There were clear differences between fields in the ped size distributions (Figure 64). Bawdeswell 26, PF5, Papworth 728 and QV Oaks had very high proportion (61-67 %) of peds < 2 mm and therefore had a very fine-structured ridge. Soils with low organic matter percentage and a high proportion of sand might be expected to produce few large peds and this was clearly the case with Bawdeswell 26 and PF5. QV Oaks had a high organic matter percentage but a loamy sand soil in two replicates and a clay loam in the third. In the loamy sand areas of this field, 74 % of the soil had a ped size < 2 mm, whilst in the clay loam area it was only 46 %. The coarsest seedbeds were produced on clay soils (Stevenson) which had only c. 23 % of soil in the finest ped size class. Mean ped size was 6.9 mm and the distribution between fields is shown in Figure 65.

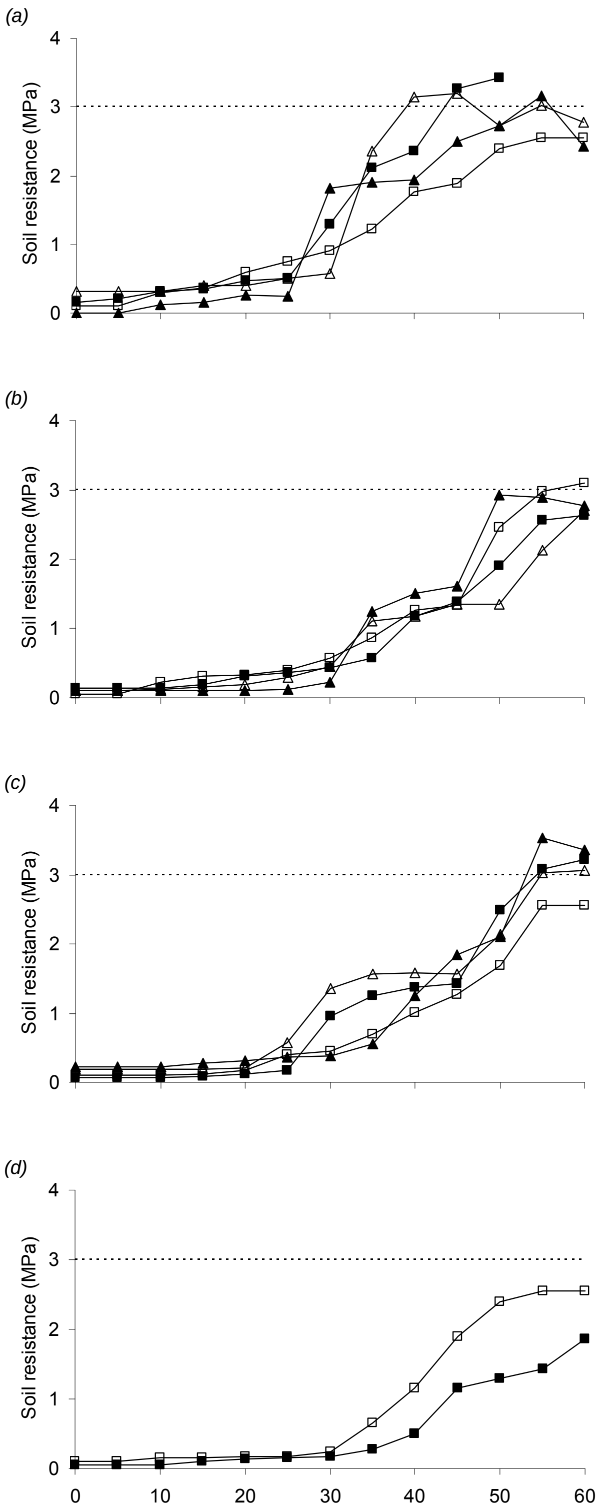

FIGURE 62. SOIL RESISTANCE AT PLANTING IN 2009. (A) BAWDESWELL 26 (■), GARRODS NORMANS (□), HARROLDS 1 (▲), HARROLDS 2 (△); (B) PAPWORTH 22 (■), PAPWORTH 904 (□), LUDHAM R7 (▲), SUTTON 164 (△); (C) HBS NE5 (■), OVERTON TOOKE (□), OVERTON SEWAGE (▲), CRANE 15 (△); (D) SPEARHEAD WASHPIT (■), SPEARHEAD S. COMMON (□). DOTTED LINE SHOWS 3 MPA LIMIT FOR ROOT GROWTH.

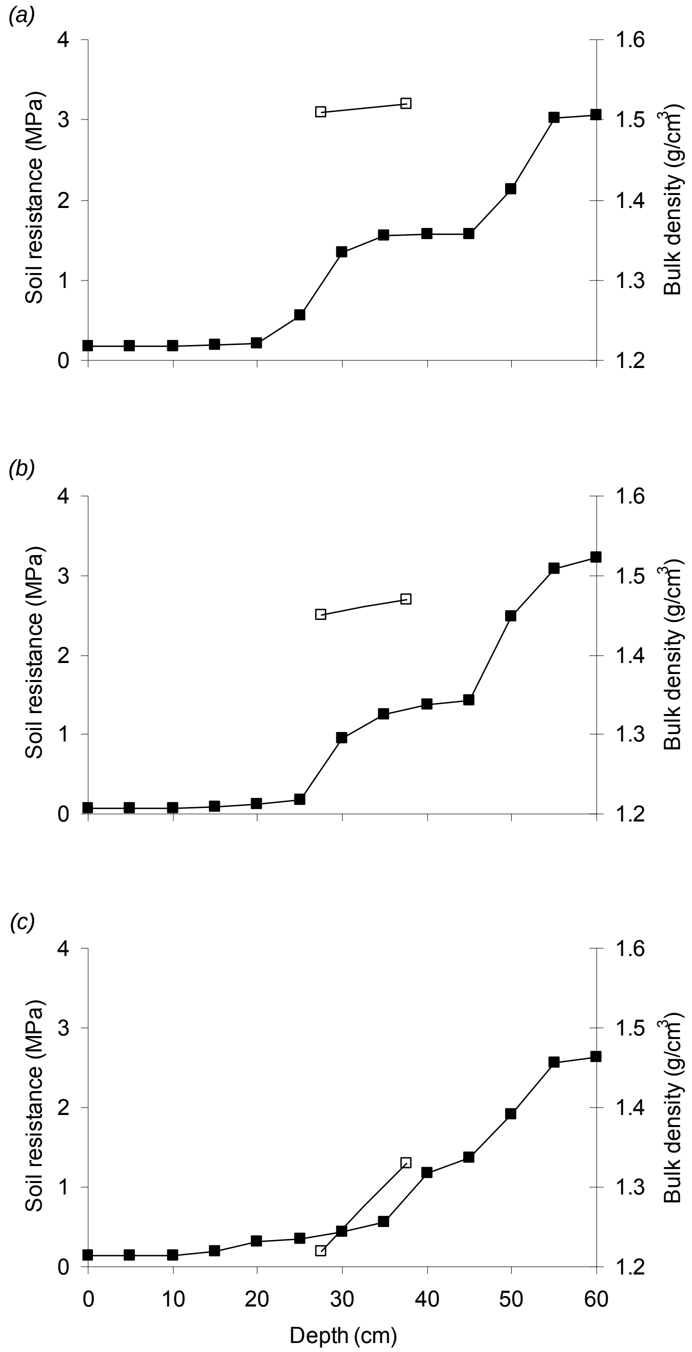

FIGURE 63. SOIL RESISTANCE(■) AND BULK DENSITY (□) IN (A) CRANE 15; (B) PAPWORTH 22; (C) HBS NE5 IN 2009.

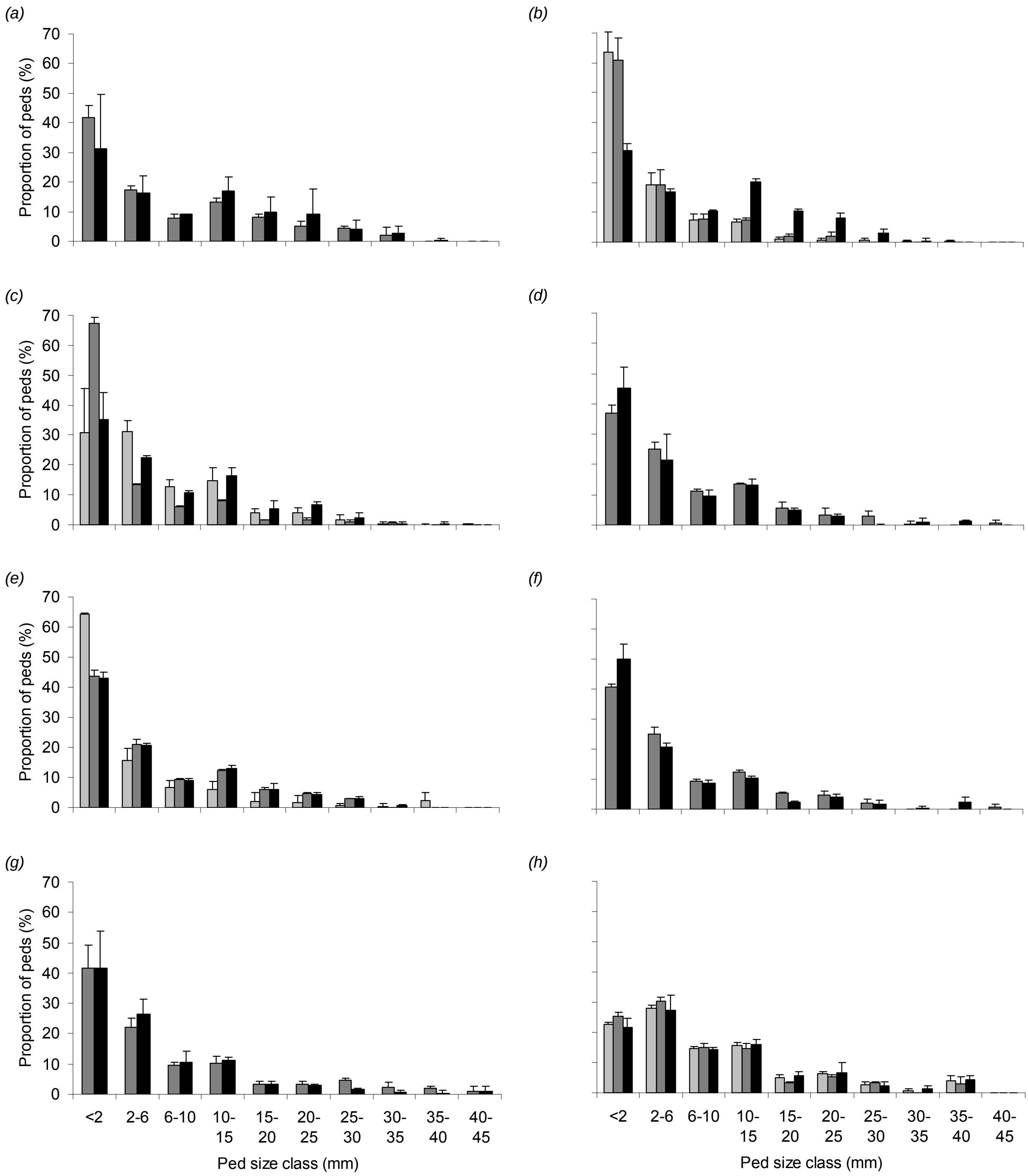

FIGURE 64. PED SIZE DISTRIBUTION (PROPORTION W/W) WITHIN RIDGES IN 2009. (A) HARROLDS 1 (■), HARROLDS 2 (■); GARRODS NORMANS (■), (B) PF5 (■), BAWDESWELL 26 (■); (C) PAPWORTH 22 (■), PAPWORTH 728 (■), PAPWORTH 904 (■); (D) LUDHAM R7 (■), SUTTON 164 (■); (E) SPEARHEAD WASHPIT (■), SPEARHEAD S. COMMON (■), QV OAKS (■); (F) OVERTON SEWAGE (■), OVERTON TOOKE (■); (G) HBS NE5 (■), CRANE 15 (■); (H) STEVENSON BRACKLEYS (■), STEVENSON WOOD (■), STEVENSON BLACKLANDS (■).

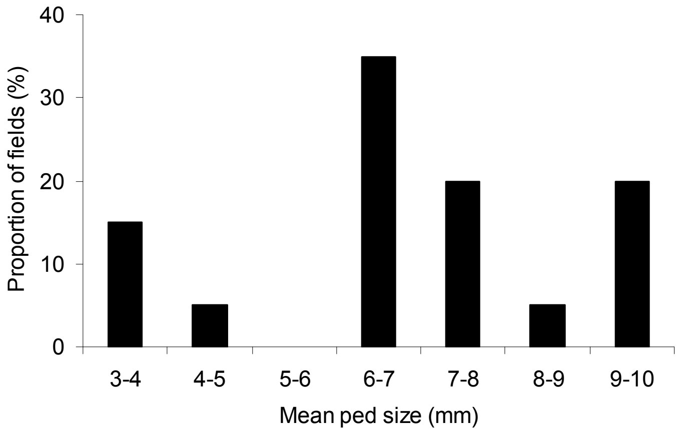

FIGURE 65. PROPORTION OF FIELDS IN 2009 WITH RESPECT TO THEIR MEAN PED SIZE.

4.9. Commercial fields 2010

4.9.1. Texture and organic matter percentage

Textural analysis of soil samples from three composite samples from 25-35 cm from all four Replicates at each Location in each field showed that there was a range in texture from loamy sand to clay, with clay contents ranging from 10 to 38 % and clay + silt from 21 to 86 %, whilst organic matter percentage varied between 1.1 and 2.6 % (Table 61), and therefore similar to fields in 2009.

Field	Soil Association†	Texture‡	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)
Oxnead 2	Wick 2	SL	55	31	14	1.5
Booton 32	Newport 3	SL	66	19	15	1.1
Pap Whitwell	Wick 2	CL	43	38	19	2.1
Pap Horse	871c	CL	37	43	20	1.8
Crane 6	Wick 2	SL/SZL	50	34	17	1.4
Crane 123	Wick 2	SZL	49	36	16	1.3
Lamb Home	Wick 2	SZL	45	40	15	1.4
Lamb N8	Wick 2	SL	61	28	12	1.7
GFP 15	Barrow	SL	59	28	14	1.7
Lowgrounds	Wick 2	SZL	45	38	17	1.4
Walsham W	Wick 3	SL	54	31	15	1.5
Joice Champion	Burlingham 3	SL	69	15	16	1.4
Joice Norton	Burlingham 3	SL	68	19	13	2.5
Joice Horse Pit	Burlingham 3	SL	69	18	13	2.2
Joice Wash Pit	Burlingham 3	SL	66	17	17	1.4
Harrolds	Barrow	SCL/SL	66	17	18	1.3
Preva 20 Ac	Wick 2	SZL	46	39	15	1.7
Preva Shoot	Wick 2	SZL	45	39	17	1.6
Spear Larches	Newport 4	SL	75	13	12	1.3
Spear 36 Ac	Worlington	SL	66	17	17	1.3
Spear Ireland	Worlington	LS/SL	80	11	10	1.5
Spear Gravel Pit	Burlingham 3	SL/SCL	66	16	18	1.4
Thomp Reckerby	Wisbech	CL	21	48	31	2.5
Thomp Grove	Wisbech	SZL/CL	32	50	18	2.2
Stevenson Grove	Stretham	C	20	43	37	2.6
Stevenson 18 Ac	Stretham	ZC	15	48	38	2.6
Mean			53	30	18	1.7

†Soil Survey of England and Wales (1983) ‡S = sand, C = clay, Z = silt, L = Loam(y)

TABLE 61. SOIL ASSOCIATION, TEXTURAL CLASSIFICATION, CLAY, SILT AND ORGANIC MATTER PERCENTAGES BASED THE AVERAGE OF SAMPLES TAKEN FROM 25-35 CM DEPTH FROM ALL 12 LOCATIONS IN EACH FIELD IN 2010

4.9.2. Bulk density

4.9.2.1. Density at cultivation depth and ridge density

Mean soil bulk densities at cultivation depth varied from 1.18 to 1.55 g/cm3 and, in general, the bulk density was lower at 25-30 cm depth than at 30-35 cm (Table 62). However, there were fine sandy silt loam soils (e.g. Crane 6, Crane 123 and Lamb N8) which had similar (high) bulk density at both depths sampled. Ridge bulk densities ranged from 0.96 to a very high 1.27 g/cm3 (Table 62). Low ridge density could be achieved without destoning with high density at cultivation depth (e.g. Crane 123) or very high ridge density at moderate density at 30 cm. The range in ridge and deeper profile bulk density across the four Joice fields on the same textured soil using the same cultivation regime is particularly interesting.

Field	Ridge density (g/cm3)	Density 25-30 cm (g/cm3)	Density 30-35 cm (g/cm3)	Mean density 25-30 cm (g/cm3)
Oxnead 2	0.96	1.27	1.37	1.32
Booton 32	1.09	1.37	1.48	1.43
Pap Whitwell	1.02	1.23	1.34	1.28
Pap Horse	1.01	1.19	1.38	1.29
Crane 6	1.16	1.49	1.54	1.51
Crane 123	1.00	1.53	1.56	1.55
Lamb Home	1.06	1.29	1.39	1.34
Lamb N8	1.01	1.46	1.50	1.48
GFP 15	1.09	1.20	1.26	1.23
Lowgrounds	1.07	1.33	1.31	1.32
Walsham W	1.06	1.38	1.52	1.45
Joice Champion	1.27	1.33	1.37	1.35
Joice Norton	1.18	1.20	1.23	1.21
Joice Horse Pit	1.06	1.16	1.19	1.18
Joice Wash Pit	1.23	1.32	1.42	1.37
Harrolds	1.22	1.36	1.52	1.44
Preva 20 Ac	1.09	1.21	1.30	1.26
Preva Shoot	1.10	1.22	1.31	1.27
Spear Larches	1.07	1.25	1.33	1.29
Spear 36 Ac	1.11	1.20	1.32	1.26
Spear Ireland	1.17	1.34	1.49	1.42
Spear Gravel Pit	1.04	1.37	1.49	1.43
Thomp Reckerby	0.95	1.32	1.42	1.37
Thomp Grove	1.03	1.19	1.25	1.22
Stevenson Grove	1.00	1.23	1.29	1.26
Stevenson 18 Ac	0.95	1.22	1.28	1.25
Mean	1.08	1.29	1.38	1.34
S.E. (25 D.F.)	0.086	0.099	0.105	0.099

TABLE 62. RIDGE DENSITY AND BULK DENSITY AT 25-30 AND 30-35 CM DEPTHS IN 2010

Across both 2009 and 2010, there was no significant relationship between bulk density at cultivation depth and either the proportion of sand or clay (Figure 66a) but there was a significant negative relationship between bulk density and organic matter content, with around 46 % of the variation in bulk density being explained by differences in organic matter content (Figure 66b).

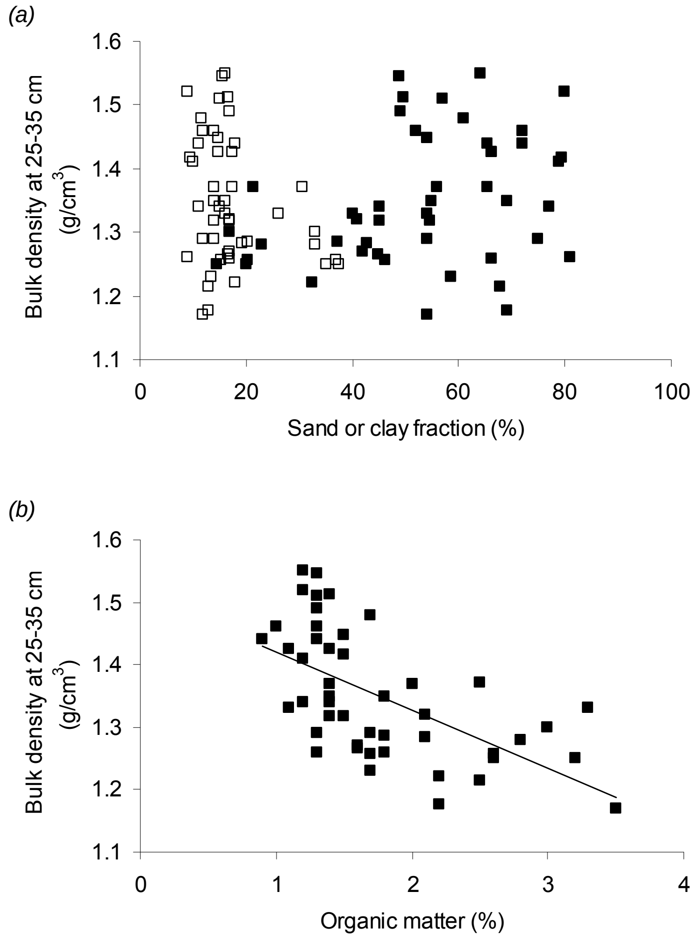

FIGURE 66. EFFECT OF (A) SAND AND CLAY AND (B) ORGANIC MATTER PROPORTION ON BULK DENSITY AT CULTIVATION DEPTH, ALL SITES 2009-2010. SAND, ■; CLAY, □. LINEAR RELATIONSHIP SHOWN IN (B): Y = -0.0933X + 1.51, %VAR = 45.6.

4.9.2.2. Relationship between bulk density and soil water content at cultivation

In 25 out of the 26 fields sampled in 2010, there was a significant positive linear correlation between the mean soil bulk density at 25-35 cm depth and the water content at cultivation but the magnitudes and relative changes in bulk density differed between fields (Figure 67, Figure 68, Figure 69,Table 63). On average, only 57 % of the variation in bulk density was explained by differences in the water content at cultivation, so clearly other factors play an important role in determining bulk density. However, the overall mean and the variation in the slopes between fields of the relationships between bulk density at cultivation depth and soil water content at cultivation was shallower in 2010 (0.0214 ± 0.00555 g/cm3/%) than in 2009 (0.0262 ± 0.00702 g/cm3/%). There was, as in 2009, no overall relationship between bulk density at cultivation depth and soil water content at cultivation when examining the entire data set from 2010. The soil textures ranged from loamy sand (10 % clay) to clay (37 % clay), with a mean clay content of 18 ± 6.9 % and silt content of 30 ± 12.2 %. Small changes in the sum of these two textural units influence cultivatability to a much greater extent than sand. However, the four fields at Joice demonstated the possible value of organic matter in terms of cultivatability. The textural breakdown was almost identical across all fields, yet the bulk density from ridge down to 30 cm was higher in the two fields) with lower organic matter (Champion, Wash Pit) than the other two fields (Norton, Horse Pit) which had an average of 2.2-2.5 %. The slope of the relationship between bulk density at cultivation depth and soil water content at cultivation was also lower in the two fields with higher organic matter than the other pair (Table 63).

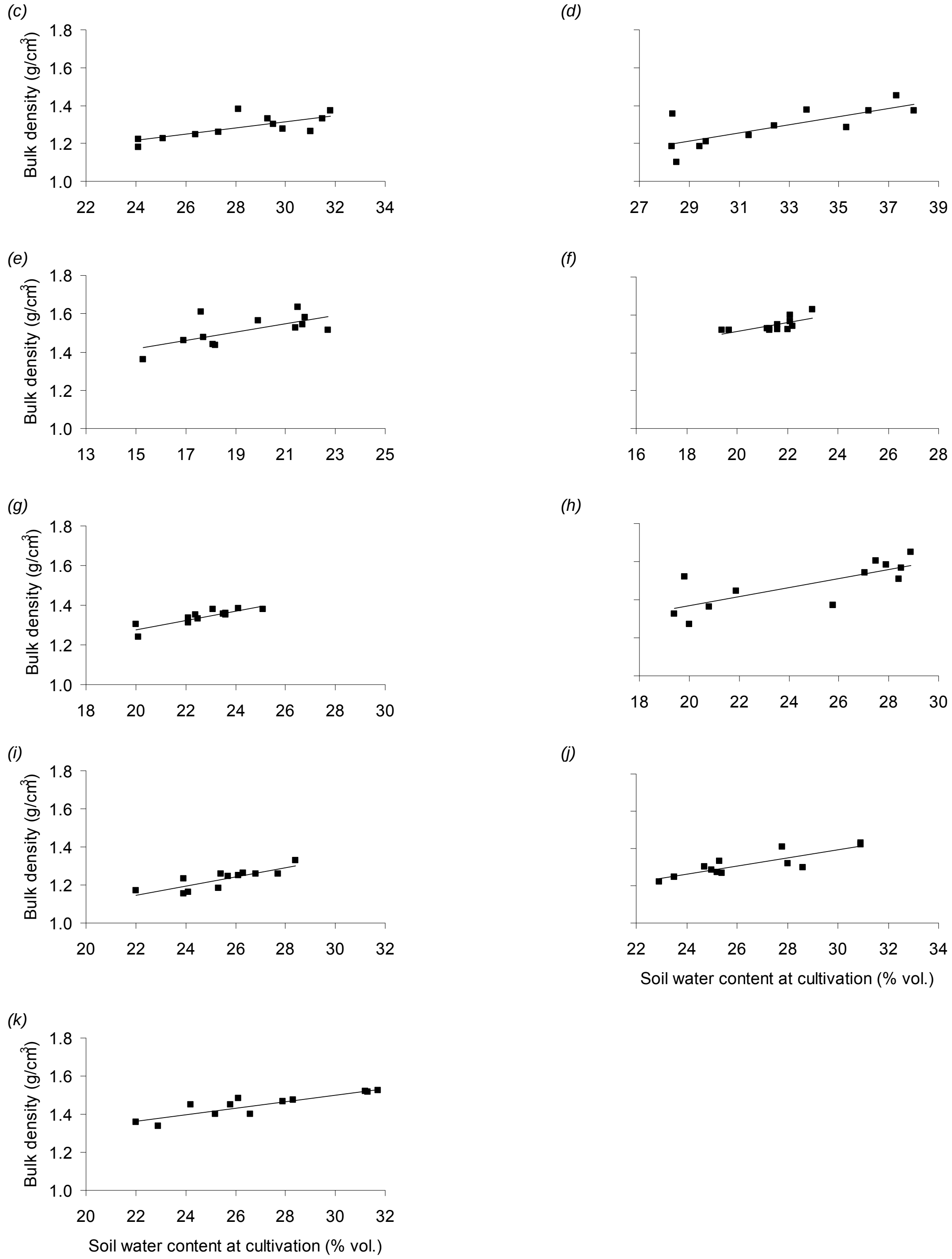

Figure 67. Effect of soil water content at cultivation on bulk density at 25-35 cm depth in 2010. *(a)* Oxnead 2; *(b)* Booton 32; *(c)* Pap Whitwell; *(d)* Pap Horse; *(e)* Crane 6; *(f)* Crane 123; *(g)* Lamb Home; *(h)* Lamb N8; *(i)* GFP 15; *(j)* Lowgrounds; *(k)* Walsham W.

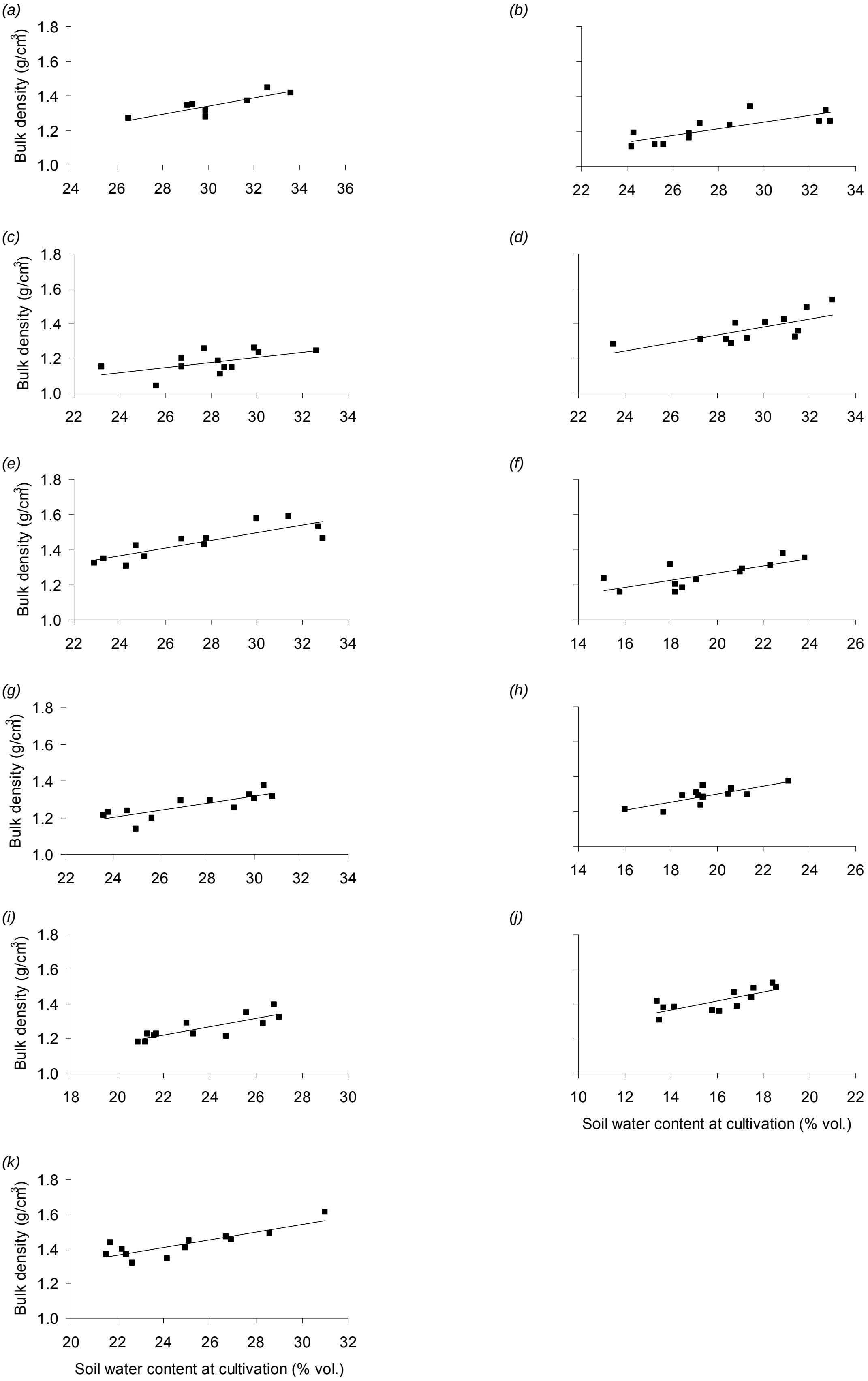

FIGURE 68. EFFECT OF SOIL WATER CONTENT AT CULTIVATION ON BULK DENSITY AT 25-35 CM DEPTH IN 2010. (A) JOICE CHAMPION; (B) JOICE NORTON; (C) JOICE HORSE PIT; (D) JOICE WASH PIT; (E) HARROLDS; (F) PREVA 20 AC; (G) PREVA SHOOT; (H) SPEAR LARCHES; (I) SPEAR 36 AC; (J) SPEAR IRELAND; (K) SPEAR GRAVEL PIT.

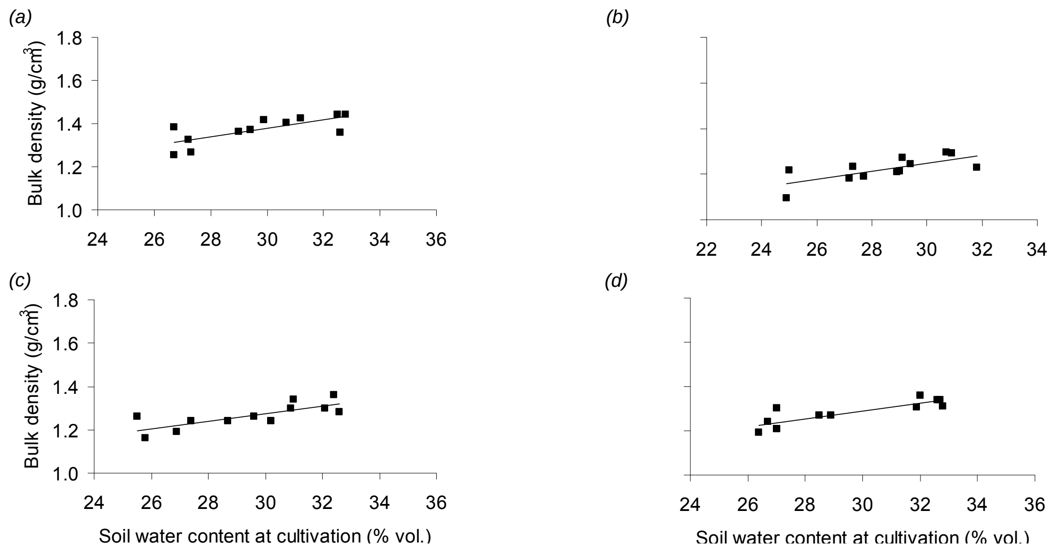

FIGURE 69. EFFECT OF SOIL WATER CONTENT AT CULTIVATION ON BULK DENSITY AT 25-35 CM DEPTH IN 2010. *(A)* THOMP RECKERBY; *(B)* THOMP GROVE; *(C)* STEVENSON GROVE; *(D)* STEVENSON 18AC.

							Range in water content (%)	
Field	**Slope**	**S.E.**	**Fprob**	**Intercept**	**S.E.**	**VAR**	**Min**	**Max**
Oxnead 2	0.0236	0.00619	0.003	0.71	0.161	55.1	21.4	30.1
Booton 32	0.0262	0.00751	0.006	0.75	0.194	50.3	23.5	28.2
Pap Whitwell	0.0167	0.00451	0.004	0.81	0.128	53.7	24.1	31.8
Pap Horse	0.0212	0.00601	0.005	0.60	0.196	50.9	28.3	38.0
Crane 6	0.0214	0.00808	0.024	1.10	0.158	35.3	15.3	22.7
Crane 123	0.0237	0.00811	0.015	1.04	0.174	40.7	19.4	23.0
Lamb Home	0.0240	0.00425	<0.001	0.79	0.097	73.8	20.0	25.1
Lamb N8	0.0244	0.00638	0.003	0.88	0.159	55.3	19.4	28.9
GFP 15	0.0248	0.00532	<0.001	0.60	0.136	65.4	22.0	28.4
Lowgrounds	0.0223	0.00400	<0.001	0.73	0.107	73.2	22.9	30.9
Walsham W	0.0169	0.00276	<0.001	0.99	0.075	76.8	22.0	31.7
Joice Champion	0.0240	0.00610	0.008	0.62	0.185	67.5	26.5	33.6
Joice Norton	0.0186	0.00451	0.002	0.70	0.127	59.2	24.2	32.9
Joice Horse Pit	0.0152	0.00717	NS	0.75	0.202	24.1	23.2	32.6
Joice Wash Pit	0.0237	0.00736	0.009	0.67	0.218	45.9	23.5	33.0
Harrolds	0.0223	0.00445	<0.001	0.83	0.123	68.7	22.9	32.9
Preva 20 Ac	0.0207	0.00560	0.004	0.85	0.110	53.6	15.1	23.8
Preva Shoot	0.0192	0.00447	0.002	0.74	0.123	61.5	23.6	30.8
Spear Larches	0.0230	0.00572	0.002	0.84	0.112	57.9	16.0	23.1
Spear 36 Ac	0.0236	0.00526	0.001	0.70	0.125	63.5	20.9	27.0
Spear Ireland	0.0260	0.00714	0.005	1.00	0.115	52.6	13.4	18.6
Spear Gravel Pit	0.0220	0.00441	<0.001	0.88	0.110	68.4	21.5	31.0
Thomp Reckerby	0.0201	0.00573	0.006	0.78	0.170	50.8	26.7	32.8
Thomp Grove	0.0173	0.00535	0.009	0.73	0.153	46.2	24.9	31.8
Stevenson Grove	0.0174	0.00452	0.003	0.75	0.133	55.6	25.5	32.6
Stevenson 18 Ac	0.0178	0.00343	<0.001	0.75	0.101	70.3	26.4	32.8
Mean	0.0214			0.79		56.8	22.0	29.5
S.E. (25 D.F.)	0.00313			0.130		12.42	3.81	4.46

TABLE 63. SUMMARY 2010: SLOPE OF BULK DENSITY VS SOIL WATER CONTENT RELATIONSHIP ($G/CM^3/\%$), SIGNIFICANCE OF RELATIONSHIP (FPROB), INTERCEPT OF RELATIONSHIP, PERCENTAGE VARIANCE ACCOUNTED FOR (VAR) AND RANGE IN SOIL WATER CONTENT AT CULTIVATION. S.E. BASED ON 10 D.F.

Combining the data from 2009 and 2010, the slope of bulk density versus soil water content relationship (g/cm3/%) was unaffected by soil clay content (Figure 70a). However, the combined proportion of clay + silt was negatively correlated with the slope but less than 30 % of the variation in slope was accounted for (Figure 70b). There was a more significant and closer-fitting negative linear relationship ($P < 0.001$) between the slope and organic matter percentage (Figure 70c).

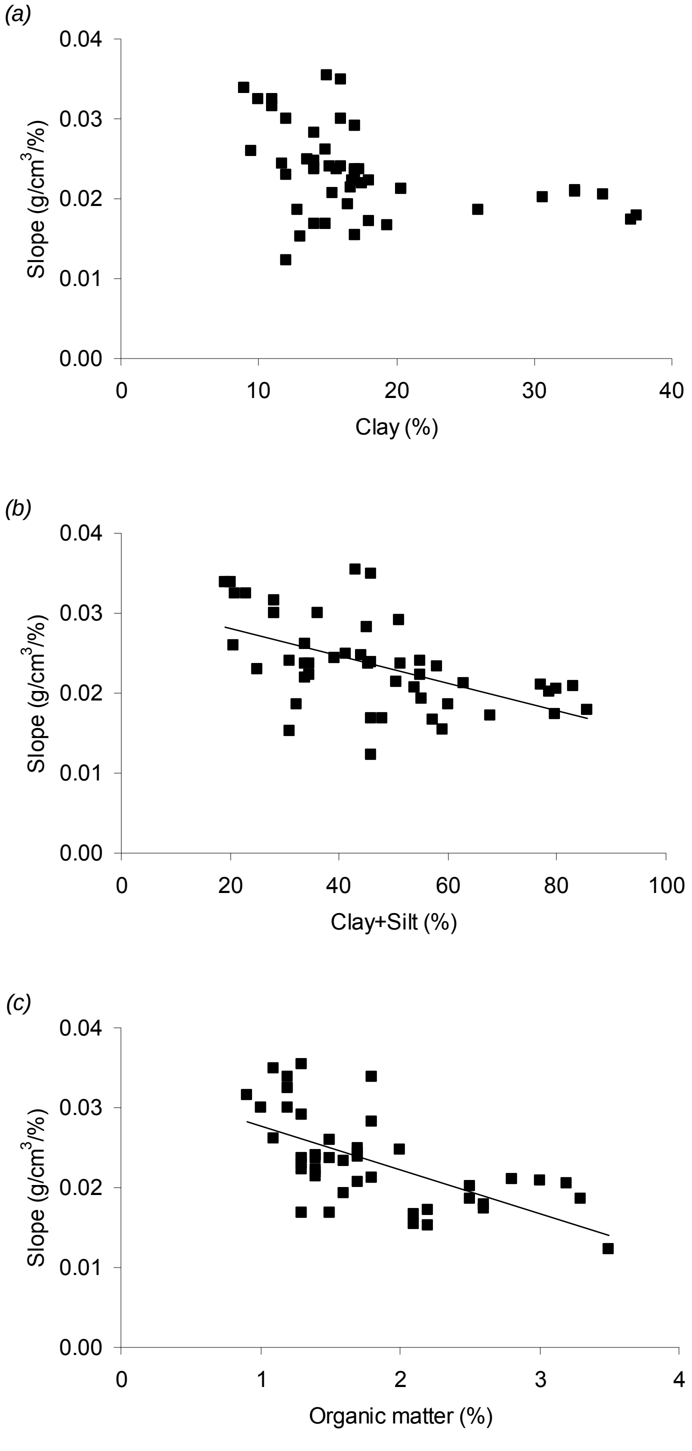

Figure 70. Effect of (a) clay, (b) clay+silt and (c) organic matter proportion on slope of relationship between bulk density and soil water content at cultivation in both 2009 and 2010. Linear relationship shown in (b): $y = -0.00017x\ (\pm 0.0000344) + 0.032$, %VAR = 29.0; (c): $y = -0.0055x\ (\pm 0.00103) + 0.033$, %VAR = 43.7

4.9.3. Soil resistance

Soil resistance was only measured in two-thirds of the fields in 2010 owing to the difficulty of sampling close enough to planting. Figure 71 shows the resistance of the fields surveyed. Booton 32 had a very noticeable pan between 40 and 45 cm below the top of the ridge (c. 30-35 cm from a flat surface) indicating the historical cultivation depth (Figure 71a). The two Papworth fields (Whitwell and Horse) had similar, good resistances throughout the profile (Figure 71b). Both Crane fields had moderate resistances at cultivation depth which reflected the bulk density data (Figure 71c). GFP 15 had a very large increase in resistance between 30 and 35 cm depth indicating a possible pan created by the destoner (Figure 71d). Spearhead Larches and Gravel Pit both exceeded 3 MPa less than 50 cm below the top of the ridge, whilst Ireland had a very strong resistance within the ridge (Figure 71e). The clay loam field at Thomp Reckerby had compaction below 30 cm compared with the sandy silt loam at Thomp Grove and this affected crop growth noticeably even though the resistances throughout the profile were generally low on these two fields.

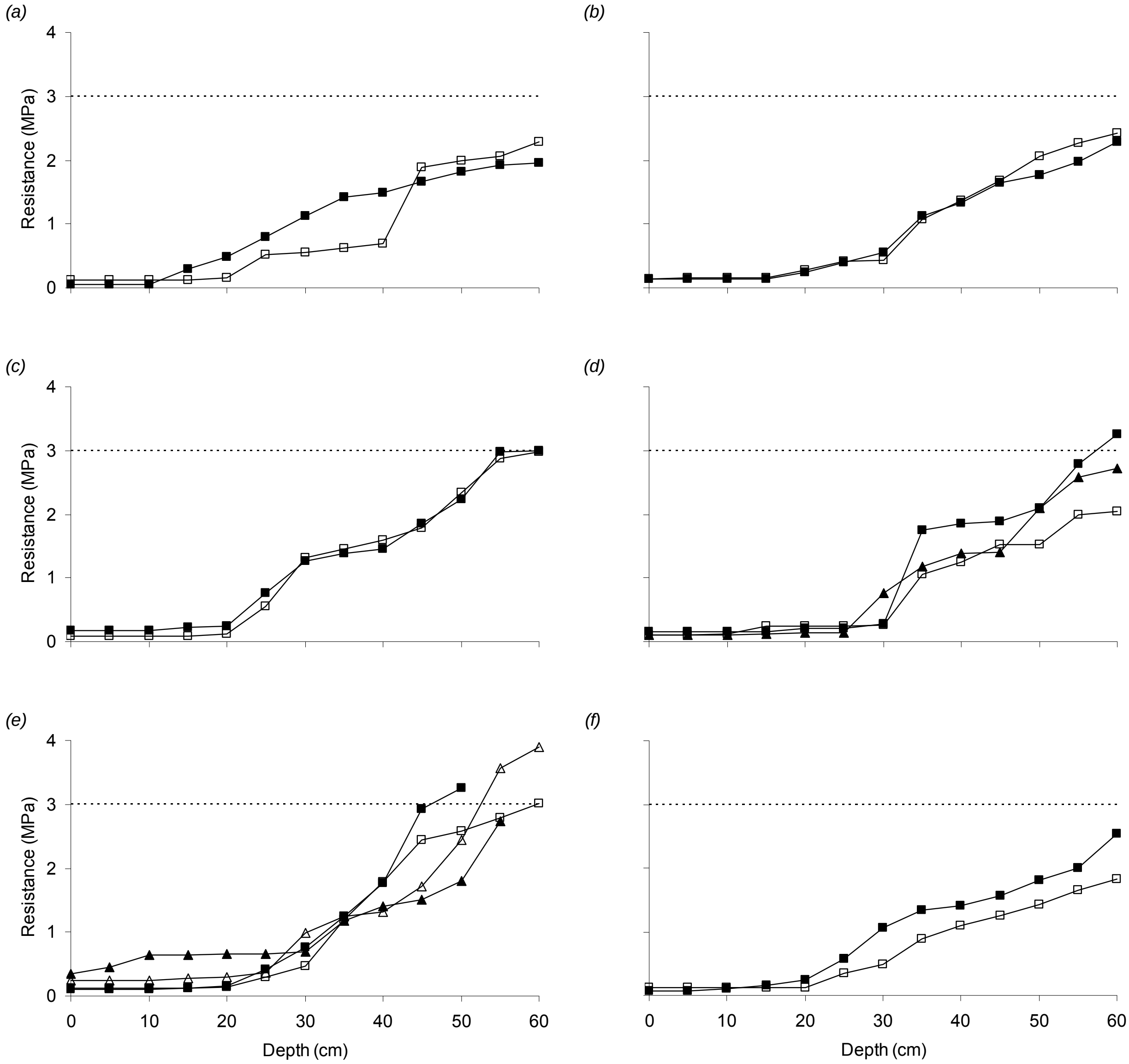

FIGURE 71. SOIL RESISTANCE AT PLANTING IN 2010. (A) OXNEAD 2 (■), BOOTON 32 (□); (B) PAP WHITWELL (■), PAP HORSE (□); (C) CRANE 6 (■), CRANE 123 (□); (D) GFP 15 (■), LOWGROUNDS (□), WALSHAM W (▲); (E) SPEAR LARCHES (■), SPEAR 36 AC (□), SPEAR IRELAND (▲), SPEAR GRAVEL PIT (△); (F) THOMP RECKERBY (■), THOMP GROVE (□). DOTTED LINE SHOWS 3 MPA LIMIT FOR ROOT GROWTH.

4.9.4. Ped size distribution

As in 2009, there were clear differences between fields in the ped size distributions (Figure 72 and Figure 73). The loamy sand fields (e.g. Spear Larches, Spear Ireland) had very high proportion (70-80 %) of peds < 2 mm and therefore had a very fine-structured ridge. Soils with low organic matter percentage and a high proportion of sand might be expected to produce few large peds and this was clearly the case with Spear Larches, Spear Ireland, Harrolds and both Preva fields. In 2009, the coarsest seedbeds were produced on clay soils (Stevenson), and whilst the clay soils were again cloddier than sandy soils in 2010, there were a number of fields of intermediate texture (i.e. sandy silt loam) that produced a high proportion of large (> 35 mm) clods e.g Harrolds, Lowgrounds and Walsham W. The latter three crops were destoned using a larger pitch web as they were destined for processing rather than packing, so it might be expected that larger clods would remain in the ridge at planting. However, these clods were still present at the end of July.

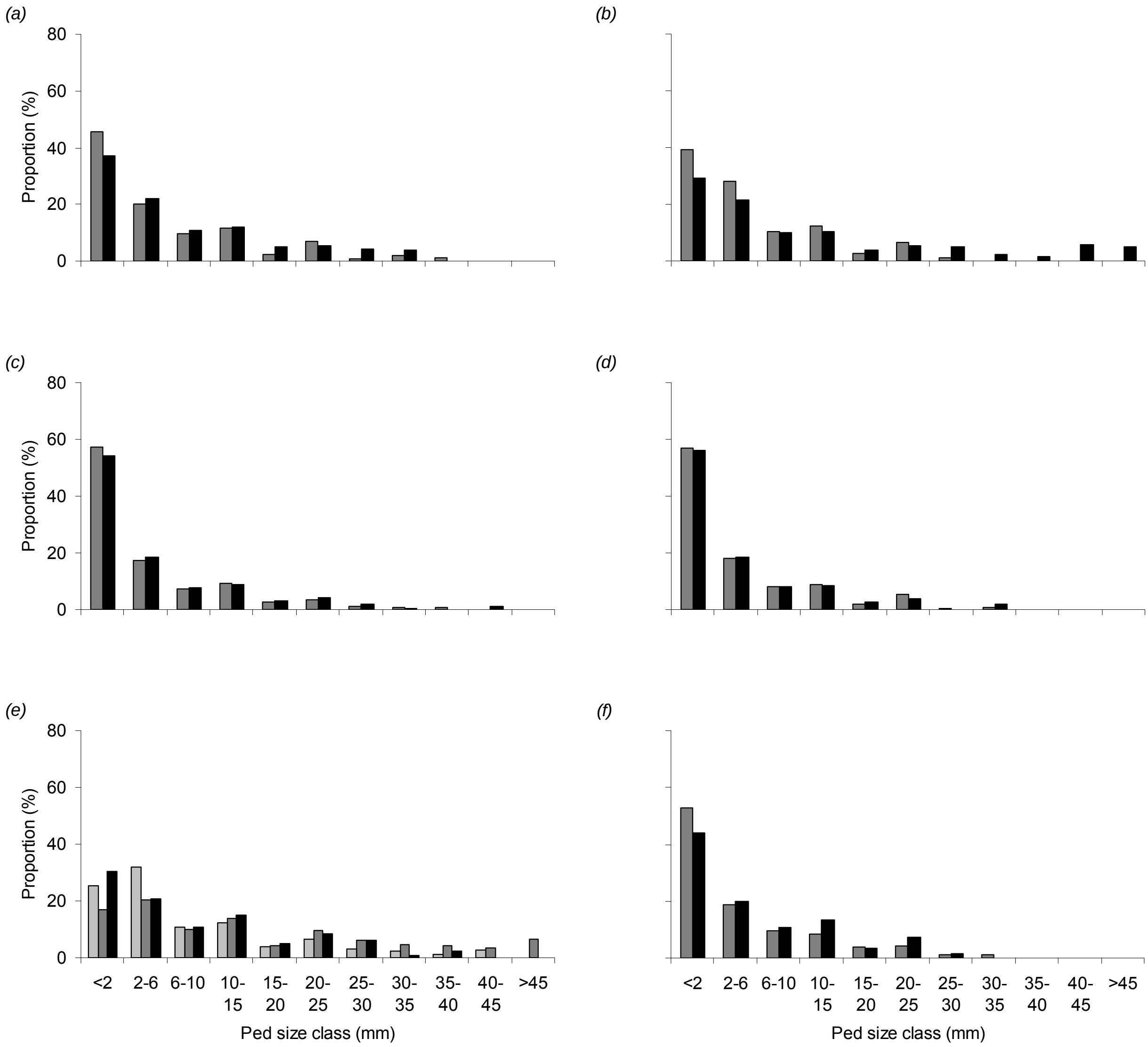

FIGURE 72. PED SIZE DISTRIBUTION (PROPORTION W/W) WITHIN RIDGES IN 2010. (A) OXNEAD 2 (■), BOOTON 32 (■); (B) PAP WHITWELL (■), PAP HORSE (■); (C) CRANE 6 (■), CRANE 123 (■); (D) LAMB HOME (■), LAMB N8 (■); (E) GFP 15 (■), LOWGROUNDS (■), WALSHAM W (■); (F) JOICE CHAMPION (■), JOICE NORTON (■).

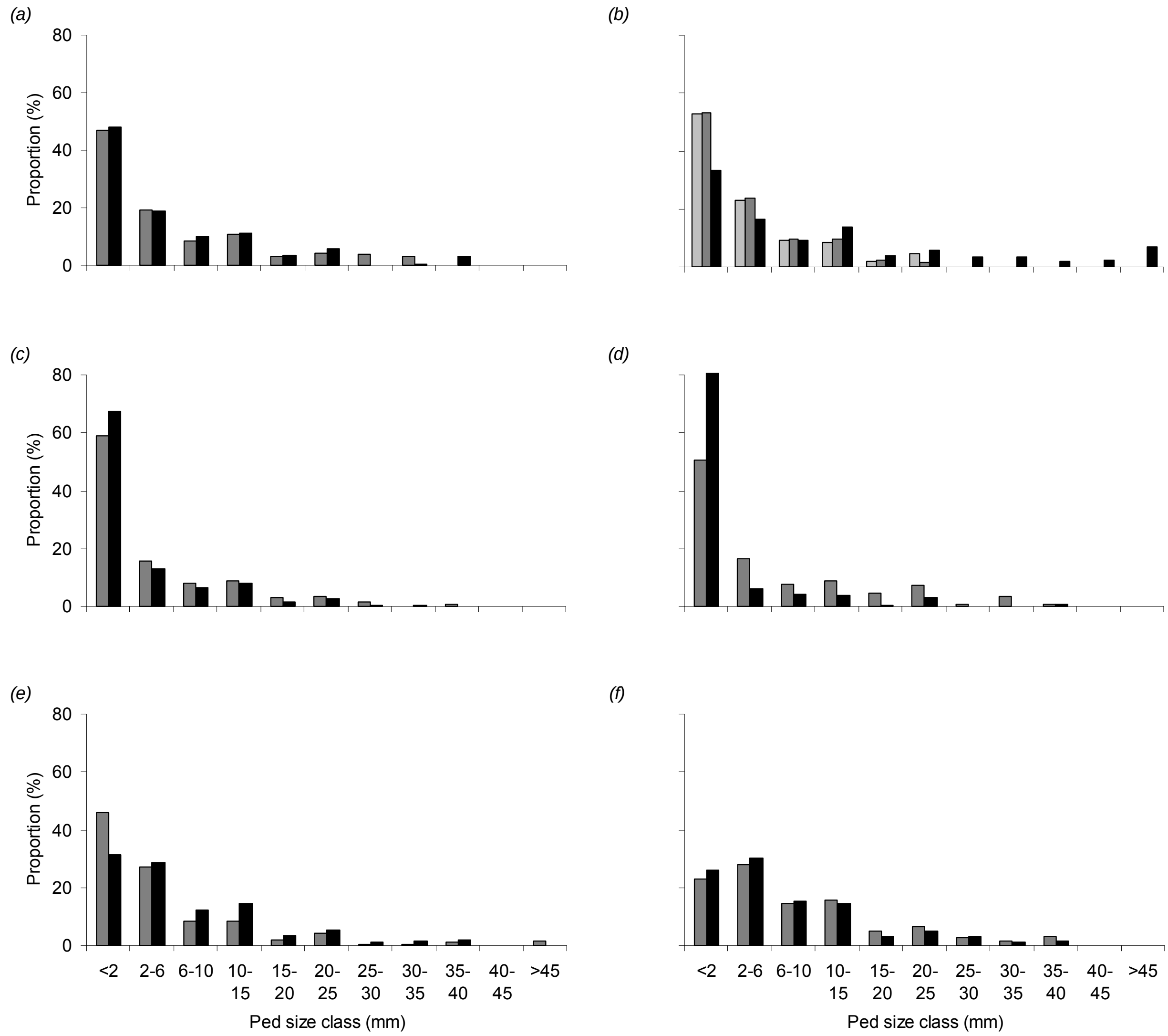

FIGURE 73. PED SIZE DISTRIBUTION (PROPORTION W/W) WITHIN RIDGES IN 2010. (A) JOICE HORSE PIT (■), JOICE WASH PIT (■); (B) HARROLDS (■), PREVA 20 AC (■); PREVA SHOOT (■); (C) SPEAR LARCHES (■), SPEAR 36 AC (■); (D) SPEAR IRELAND (■), SPEAR GRAVEL PIT (■); (E) THOMP RECKERBY (■), THOMP GROVE (■); (F) STEVENSON GROVE (■), STEVENSON 18 AC (■).

Mean ped size in 2010 (7.1 mm) was almost identical to 2009 (6.9 mm) and the distribution between fields is shown in Figure 74. The finest seedbed (mean ped size 2.9 mm) was not surprisingly created on a loamy sand (Spear Ireland), with a very coarse ridge being produced at Lowgrounds (mean ped size 15.8 mm).

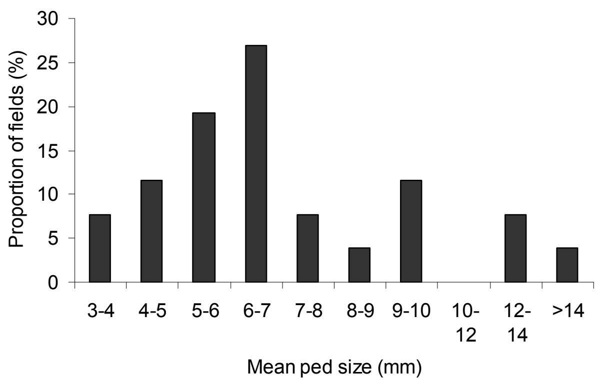

FIGURE 74. PROPORTION OF FIELDS IN 2010 WITH RESPECT TO THEIR MEAN PED SIZE.

5. Conclusions

5.1. Soil cultivation experiments

All cultivation experiments during 2008-2010 demonstrated a number of important features associated with cultivation management. There were significant increases in soil bulk density (and concomitant reductions in porosity and air capacity) at the cultivation working front where the soil was cultivated above Field Capacity rather than in a drier state. In soil cultivated whilst dry there were decreases in soil bulk density at cultivation depth during the course of the season as a consequence of loosening through root activity which were not apparent in soil cultivated whilst wet. Overall soil porosity (air- and water-holding capacity) decreased as the season progressed and was reduced by cultivating the soil whilst wet. Clod size distribution within the ridge was unaffected by most cultivation treatments but allowing ploughed or cultivated soil to dry for several days prior to final roto-tilling produced cloddier ridges. Mean clod size decreased during the season as the soil weathered and lost structure but the degradation was only slight indicating that cloddy ridges at planting are likely to remain cloddy through to harvest. Available soil water was generally decreased on a gravimetric basis in soils cultivated whilst wet. However, owing to the significant increase in bulk density caused by soil compaction, soils compacted through cultivating whilst wet had slightly higher volumetric available water holding capacities than uncompacted soils.

Penetration resistance at the cultivation front was increased in soils cultivated whilst wet and these differences increased as the soil dried, with resistances at 25 cm exceeding the limit for root penetration (3 MPa). The effect of cultivation regime on soil strength was also greater where the soils were unirrigated throughout the season than where they were irrigated. Rooting density was reduced by c. 15 % in soils cultivated whilst wet, with roots proliferating in the region above the cultivation interface as a consequence of being unable to penetrate the areas of greater soil bulk density and resistance. This reduction in rooting through cultivation would have had a greater effect on water uptake than the small observed changes in physical water availability. Cultivating soil whilst wet increased leaf and tuber water potential and stomatal resistance but the relationship between tuber and leaf water potential was unaffected by cultivation regime. This suggests that the same balance between tuber and leaf water potential was maintained even when the plant was under water stress caused by compaction. Measured soil moisture deficits in soil cultivated wet were greater than when cultivated whilst dry, mostly as a consequence of differences at the 25 cm depth, indicating a shallower zone of water uptake by crops grown in compacted soil.

The effects of soil water content at cultivation on canopy expansion and duration and yield of the crop were small and generally not statistically significant, despite there being significant differences in soil factors at cultivation depth. In one year (2008), ground cover was reduced by cultivating wet soil and this resulted in a yield decrease compared with cultivating soil in a drier state. In all years there were still significant, albeit small, differences in rooting density, stomatal resistance and leaf and tuber water potential between soils cultivated dry or wet, but these did not manifest into significant differences in yield at final harvest in two years out of three.

Seven experiments over the period 2005-2010, including three from the current project, whilst having different designs and treatments, used cultivations at different soil moisture contents to generate contrasting soil conditions. Some of these experiments also tested the effects of different amounts of N or irrigation. Considering only the treatments involving Maris Piper, over the seven experiments soil cultivation affected yield in three experiments. In 2006 and 2008 cultivating wet soils (resulting in a smeared layer at c. 25 cm below the ridge) reduced tuber FW yields by c. 10 and 5 t/ha, respectively. In 2005, yields were increased by c. 4 t/ha when the soils were cultivated wet but this was attributed to compaction caused by frequent passes with a tractor and spring-tine cultivator that was used to cultivate the soil in the dry plots before roto-ridging. In all other years, the differences between cultivating soil wet or moist were small and not significant. Thus despite cultivating soils at inappropriate moisture contents, the overall effects on yield were relatively small (i.e. an average loss of 1.8 t/ha compared with an average yield over six seasons of 58.3 t/ha). However, the experiment in 2006 showed that inappropriate cultivations can cause appreciable soil damage and this resulted in a large yield penalty. It is possible that Maris Piper is relatively tolerant of moderately poor soil conditions, however in 2010 Lady Rosetta was also included and cultivation at different soil water contents also had little effect on its yield. The soils at Cambridge have a relatively high stone content (12-15 %) and, due to history of FYM applications, have relatively high organic matter content (c. 4-5 %, although this has decreased since application ceased in 1999 when organic matter content was c. 7-8 %). There was also a considerable variation in clay content throughout most experiments (e.g. 11-18 % in Expt 2008, 17-22 % in Expt 2009a and 23-26 % in Expt 2010) so that the effect of water content may have had a greater effect in different parts of the experimental areas. It is possible that these three factors can, to a certain extent, reduce the effects of compaction, thereby minimising the effects on yield but the mechanism of this mitigation needs to be better understood.

Most of the cultivation experiments conducted between 2005 and 2010 tested the effects of two or more N application rates and in each of these experiments, N application rate significantly affected yield. In three experiments (two in 2005 and one in 2008, Table 65), tuber yields were smaller when no N was applied to crops grown on compacted soils. However, when adequate N was applied there was little difference in yield between crops grown on compacted or uncompacted soils. In 2005, there were two identical experiments conducted at sandy and clay loam textured ends of the same field. There were four levels of N and at the sandy end of the field there was no response to N where soil was cultivated wet but where soil was cultivated dry, there was a response up to the second level of N (100 kg N/ha). At the heavy end of the field, a similar effect was observed but the N response in soil cultivated dry was greater and the optimum was c. 200 kg N/ha rather than 0 kg N in soil cultivated wet. In 2006, the optimum N in soil cultivated dry was close to 0 kg N/ha, whereas it was c. 100 kg in soil cultivated wet. However, collectively over the period 2005-2010, the data suggest that for crops grown on compacted soils, yields will not be greatly increased by applying more N. In the absence of N fertilizer, the effects of cultivating soil whilst wet were both more apparent and more consistent across seasons. The data indicate that where the N application is only just adequate when soil conditions are good, there may be a yield penalty when soil conditions are poor.

	2005†	2006	2007	2008	2009	2010
Cultivated dry	57.8	57.2	58.1	68.8		
Cultivated wet	62.2	46.9	58.0	64.2		
Cultivated moist					58.8	
Cultivated at Field Capacity					60.7	
Cultivated wet					57.2	
Cultivated over-wet					59.4	
Ploughed early						55.2
Ploughed late						55.8
Non-ploughed early						56.5
Non-ploughed late						58.0
Mean	60.0	52.0	58.1	66.6	59.0	56.4
S.E. (D.F.)	1.21 (33)	2.94 (6)	1.23 (9)	1.39 (33)	1.98 (30)	1.26 (14)

†Mean of two experiments (sandy loam and clay loam soils)

TABLE 64. SUMMARY OF MAIN EFFECTS OF PRIMARY CULTIVATION ON TUBER FW YIELD > 10 MM (T/HA) IN MARIS PIPER DURING 2005-2010

	N application rate (kg N/ha)	Cultivated dry	Cultivated wet	S.E. (D.F.)
2008	0	65.7	55.8	1.39 (33)
	200	72.3	72.6	1.35 (33)†
2005‡	0	48.1	62.9	2.42 (25)
	100	57.0	60.0	
	200	61.8	64.3	
	300	64.5	61.7	

†S.E. for comparing means with same cultivation
‡ Mean of two experiments (sandy loam and clay loam soils)

TABLE 65. EFFECT OF N APPLICATION RATE AND PRIMARY CULTIVATION ON TUBER FW YIELDS > 10 MM (T/HA) IN EXPERIMENTS WITH A SIGNIFICANT EFFECT OF CULTIVATION AND A SIGNIFICANT INTERACTION BETWEEN CULTIVATION AND N APPLICATION RATE

Over both years of the survey of commercial fields, within an individual field, an increase in soil water content at cultivation was associated with greater soil bulk density at cultivation depth. There were differences in the slopes of the relationship between bulk density and soil water content between fields and some of these differences in slope could have resulted from the soil drying between initial sampling and the primary cultivation at planting. However, there would be little change in soil moisture expected at 25-30 cm depth unless the stubble was very weedy and root uptake dried the profile at depth and the time interval was usually less than one week between sampling and cultivation. There was a very large range in water content at cultivation between fields, even between and within fields with the same texture. Poorly-drained fields may remain wetter during the spring than might be expected from their water-holding capacity based on soil texture and this would obviously lead to variations in the measurements of soil water content. The slopes of the relationship between bulk density and soil water content were negatively correlated with both the combined proportion of clay and silt and the organic matter concentration in the soil in each field. Organic matter content was also negatively correlated with the bulk density at cultivation depth, suggesting that even small improvements in organic status on mineral soils with low organic carbon content would improve cultivatability. As, in many cases, there were large differences in the water content of the soil at 25-30 cm at planting in fields with similar soil texture and within fields with similar texture, the target of providing an optimum window for cultivation in terms of soil water content needs further work. With additional study, it is ultimately hoped that this information can help develop a tool which can provide a useful set of recommendations for growers when cultivating fields with different textures and organic matter concentration.

The planter experiment on sandy soil provided a useful insight into the effects of soil profile and consolidation on a number of variables. The soil was very dry at planting, even at 35 cm depth, and no compaction occurred by destoning as deep as 35 cm, which is rarely achieved when planting in spring on finer-textured soils. Soil resistance measurements showed that soil strength was reduced considerably between 30 and 40 cm depth by deep destoning. By contrast, shallow destoning resulted in a considerable quantity of stone remaining under the seed tubers which would have reduced the water holding capacity of the soil considerably and undoubtedly contributed to the lower yield in shallow-destoned plots compared with deep destoning. Compressing the soil over seed tubers following planting either through shares, moulding boards, wheels or hoods is often undertaken to reduce erosion by wind or water and to consolidate the air voids following destoning, which can make the soil too porous and unable to hold water against gravity. However, in soils with even moderate (i.e. c. 10 %) clay content, it is easy to smear the outside of the ridge with covering hoods or shares if the soil is wet. This can result in crusting or capping and delayed or erratic plant emergence. Since the soil in Expt 2009c was so dry at planting, compression might have been expected to have little detrimental effect on such a sandy soil. Nevertheless, increasing the pressure on the hood delayed emergence, even though planting depth was shallower in maximum-pressure plots. Compressing the ridge harder significantly increased initial soil density but the effect had dissipated by the end of the season. Compressing ridge profiles harder resulted in more water being shed into furrows following irrigation but had little effect on bed profiles. There was an interesting reduction in yield and increase in tuber dry matter concentration where the soil was compressed more after planting.

There were a number of important observations made regarding the differences between the two soil profiles created. Despite the provision of automatic depth control on the planter it proved difficult to achieve comparable depth of planting in ridge and bed profiles, with bed profiles being planted deeper than ridge, the converse of what might be expected. The difference in planting depth between bed and ridge profiles (3 cm) probably resulted in the delay of c. 1 day in emergence. The effects of the treatments on emergence were additive i.e. up to 3 days delay if combined (deep-destoned bed profiles with maximum compression after planting). Bed profiles had significantly higher soil bulk densities than ridge. They also resulted in a lower yield than ridge profiles, which was the opposite that might be expected on sandy soils with low water holding capacity. However, the area of considerable interest between bed and ridge profiles was in water capture and distribution across the bed following irrigation, since this should improve efficiency of water by avoiding deep drainage below furrows in ridge profiles owing to water shedding. Before irrigation, inter-row water (“furrow”) content was higher than within rows but following irrigation this difference increased and increased more where crops where grown in ridge profiles than in bed. This suggested more efficient capture of water in bed profiles than in ridge following irrigation but this was not reflected in yield and needs further study.

5.2. Irrigation experiments

Maintaining the soil at Field Capacity resulted in numerically the highest yield but there was no significant difference in yield between 0 and 20 mm SMD in Maris Piper and between 0 and 30 mm SMD in Vales Sovereign. This suggests that the most efficient irrigation schedule to follow would be to maintain soil close to 25 mm SMD throughout the season. Scheduling irrigation at a maximum soil moisture deficit of 25 mm increased yield by c. 10-16 t/ha in compaction experiments compared with unirrigated crops and this was achieved as a consequence of increased radiation use efficiency through lack of water stress rather than changes in canopy duration. Varieties had similar reductions in yield when droughted for different periods or when over-irrigated during the scab control period, so there was no evidence of differential drought or water-logging tolerance amongst the cultivars selected. In 2009, canopies of unirrigated crops maintained ground cover as long as fully-irrigated crops, despite soil moisture deficits exceeding 55 mm in unirrigated crops on one or more occasions during the season. However, in 2010, the longer irrigation was delayed, the longer canopies took to reach full cover, with unirrigated crops only reaching c. 87 % ground cover as SMD exceeded 70 mm in July. Early over-watering and to a lesser extent late over-watering caused premature canopy senescence which reduced yield. In addition to affecting canopy duration, irrigation also altered the efficiency with which absorbed radiation was converted to dry matter, so that long periods of full ground cover with high SMD could be relatively unproductive for tuber yield.

In the UK experiments, for a large part of the measurement period during June and July, Vales Sovereign had significantly higher stomatal resistance than either Hermes or Maris Piper. There were slight differences in how stomatal resistance changed under contrasting irrigation treatments in different varieties but differences in resistance between varieties were not consistently large enough to demonstrate differences in stomatal function that may have affected water use efficiency. Stomatal resistance increased to a greater extent during the day in unirrigated than irrigated crops but some observations showed that over-filling the soil with irrigation caused a temporary increase in stomatal resistance soon after the irrigation event. This contrasts with crops kept over-watered for 3 weeks after tuber initiation, which had significantly lower stomatal resistance throughout late June and July than those grown under other irrigation regimes, even 4-5 weeks after the over-irrigation period had ended. In work in Washington, USA, in a hot environment, peak stomatal resistance increased with decrease in soil water content at the beginning of the day. Wilting of leaves was apparent during the afternoons in drought treatments where water was withheld during the measurement period and this caused loss of light absorption along with a delay in reaching full ground cover as canopy expansion was restricted. Maintaining an SMD of 30 mm on hot days was sufficient to cause wilting whereas there was little wilting when the SMD was < 20 mm. Nevertheless, the CUF Irrigation Model predicted that there would be appreciable differences in water use over the full length of the season between the three irrigation regimes tested. These differences would explain the observed differences in fresh weight yield between irrigation regimes in Alturas but underestimated the yield losses between irritation treatments in Russet Norkotah and Umatilla Russet. The observations on stomatal conductance and water potential largely support the output from the CUF Irrigation Model but further measurement periods during mid-August in a similar climate would allow improvements to be made to the model as the rooting system is more developed and leaf stomatal resistance and turgor tends to be less sensitive to changes in soil water content than earlier in the season. The practice of maintaining soils close to Field Capacity to maintain maximal rates of water use in climates such as Washington will result in little or no drainage since the total rainfall in June, July and August is, on average, < 30 mm. In the UK, the frequency of days where potato evapotranspiration is > 5 mm is low (typically < 7 days per year) but more importantly, rainfall is much greater in frequency and amount (typically > 150-250 mm in June-August) and such small SMDs would lead to large amounts of drainage and a decrease in the efficiency of irrigation use.

Control of common scab was generally better where soils were kept at Field Capacity following tuber initiation, however tuber cracking in Maris Piper increased significantly when soils were maintained at Field Capacity throughout the season and where early over-watering was practiced during the scab control period. In Vales Sovereign, the incidence of superficial cracking was greater the smaller the SMD maintained but there was a much larger increase in cracking when soils were maintained very wet compared with an SMD of 10 mm. In Vales Sovereign, late over-watering also increased the incidence and severity of superficial cracking centred on lenticels. The hypothesis examined was that tuber cracking might be caused by internal hydration pressure that exceeded the retaining strength of the periderm, thereby causing a failure along one or more planes of weakness. The water potential of tubers in over-irrigated plots was very much lower in both over-watered periods than tubers from treatments with less irrigation applied, but there was no significant difference in water potential between varieties, indicating that hydration status alone was not a major cause of difference in tuber cracking. Whilst Maris Piper needs to be grown in wet soil for 3 weeks shortly after tuber initiation to produce the lowest scab infection, Vales Sovereign can be maintained at an SMD of c. 30 mm to reduce the extent of cracking since the severity of common scab infection appears to be relatively insensitive to change in SMD. Yields excluding cracking and scab rejections in Vales Sovereign were similar where the SMD was maintained between 10 and 30 mm SMD but much lower when maintained at Field Capacity. There was clear evidence from the project (e.g. lower yield, increased tuber cracking) of the risk of over-watering early in the crop's growth and, with combined more recent information on the temporal population dynamics of Streptomyces on the surface of the tubers of difference varieties (Stalham 2011), indicates that irrigation scheduling during scab control needs more careful consideration.

5.3. Tuber dry matter concentration

At final harvest, tuber dry matter concentration was largely unaffected by most treatments Unirrigated crops and those with temporary irrigation restrictions had higher tuber dry matter concentrations at various points in the season but by final harvest there were no significant differences between unirrigated and irrigated treatments. Dry matter concentration was increased at final harvest in the early over-watered regime in Expt 2009b contrary to what might be expected. Initially dry matter concentration was lower in early over-watered plots compared with other irrigation regimes but within 6 weeks of emergence was, and remained, significantly higher. The effects of over-watering on dry matter concentration could be explained by increased root death in anaerobic soils which would reduce the potential for water uptake later in the season. The findings from the group of experiments conducted in the project suggest that establishing a possible control mechanism for variation in dry matter concentration at final harvest is more difficult than predicting the directional changes in dry matter concentration resulting from restricting irrigation for short periods or following re-filling of the soil with rainfall. However, there was generally a consistently greater dry matter concentration in tubers grown in soil cultivated wet compared with soil cultivated dry, indicating that water movement into tubers may be compromised by poor water uptake from compacted soil and this is likely to occur over longer periods of time than temporary irrigation or rainfall restrictions.

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