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Final Report

Management of tuber water status to reduce bruising

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2. Summary

In order to test the hypothesis that tuber hydration status plays a major role in determining the susceptibility of a tuber to blackspot bruising and internal damage on impact with a hard surface, BPC Project R263 examined the effect of water supply, soil compaction, defoliation and root cutting in six experiments at Cambridge University Farm over the period 2004-2007.

There was significant blackspot bruising in all experiments involving Lady Rosetta. In three out of four seasons, irrigation regime had no effect on bruising at final harvest when the crops were fully senesced. In one season, crops kept fully irrigated throughout the season had more bruising at final harvest than crops kept unwatered. Short or more prolonged periods of water stress increased bruising early in the season compared with maintaining soils with a low soil moisture deficit but this was transitory and once re-hydrated, tubers generally bruised similarly at the end of the season than if they had been maintained closer to hydrated for most of the season by full irrigation. In experiments with Maris Piper, where blackspot bruising was less prevalent than in Lady Rosetta, there was no consistent effect of irrigation regime on bruising at final harvest.

There was no clear evidence that tuber water potential (WP) was the sole or major controlling factor in bruise susceptibility when examining all data within one variety across the season. There were large increases in bruising during September in Lady Rosetta in one experiment across all treatments whereas tuber WP was low (i.e. hydrated) at this stage. Bruises deepened as well as becoming more numerous during September, indicating that a) the forces of impact were penetrating further into the peri-medullary zone and/or b) that internal tissues were becoming weaker during this period. From the experiments conducted, there appears to be a time course of development of blackspot bruising within a particular season in terms of developing the biochemical enzyme-substrate reaction components which may alter any relationship between bruising and tuber WP. A closer examination of hydration status over shorter time periods (e.g. 1 week down to every 2 hours) showed that the directional changes in tuber WP were reflected in similar changes in bruising (which supported the hypothesis of Smittle *et al.* 1974) but the magnitude of the change in bruising with changes in WP varied over time when the period between measurement was greater than weekly. Sampling tuber WP frequently (every 2 hours) during the day demonstrated that changes approximately equivalent to the range encountered across the season can occur within one day if the evapotranspiration demand is high and the tubers start the day in a hydrated status, so the time of sampling or harvesting could alter bruising susceptibility. The shorter the time intervals between sequential measurements of tuber WP and bruising, the closer seems to be the correlation between these two variables. This implies that point measurements of tuber water status of an individual crop are unlikely to be able to predict the incidence and severity of blackspot bruising during the season but that dehydration of tubers over a short period of time can increase the risk of bruising considerably. Tuber cracking in Smith's Comet was decreased as tuber WP increased (i.e. tubers became more hydrated), which also supports the hypothesis of Smittle *et al.* (1974). Soil compaction did not alter bruising significantly in Maris Piper.

The common grower practice (or belief) of a single irrigation event immediately prior to desiccation being useful in reducing bruising therefore has little scientific evidence to support its use, unless harvesting occurs shortly after defoliation, when wet soil acts as a cushion for tubers on harvester webs. Tuber WP in crops irrigated post-defoliation decreased faster (i.e. became hydrated more quickly) than those left with intact foliage but the magnitude of the differences created was small and not reflected in bruising sensitivity.

Mechanically defoliating a crop just prior to the onset of senescence following a period of high evapotranspiration demand caused a significant increase in blackspot bruising compared with crops allowed to senesce naturally and this occurred in all crops, irrespective of the soil moisture deficit at the time of defoliation. There was a smaller, but still significant, effect from defoliating when ground covers had decreased to 50 %. This effect appeared to be totally unrelated to changes in tuber turgor and the differences in bruising were still evident several weeks later.

3. Experimental Section

Introduction

The various forms of tuber bruising cause serious losses to all sectors of the industry every year. The BPC National Bruising Survey 2004 (BPC 2004) stated that the cost to growers was £199/ha or £26M overall. The cost to purchasers (both processing and packing) attributed to bruising is massive and is difficult to accurately estimate. When purchasers reject or downgrade loads they may incur the cost and time of re-scheduling, factory downtime and defect removal. One packer responding to the survey put the annual cost of bruising to them at £2M and one processor at £1M. The BPC estimated the industry as a whole could be losing in the region of £100M as a result of bruising. 2003 was a year in which bruising caused serious losses in all market sectors in the UK, including many salad and small potato crops. This occurrence surprised many by its severity and followed years in which bruising had been less of a problem. As a result, bruising has become a significant research priority again. In pursuing possible causes through discussions with many scientists but particularly those at Washington State University, it has become clear that one key factor may be the hydration status of the tuber, mediated through its effects on tissue strength and elasticity, and this has to be related to bruise susceptibility and management practices, especially those related to soil water availability.

Susceptibility is known to depend on both physical and biochemical characteristics of the tuber. Blackspot bruising is thought to be the result of cell damage leading to decompartmentalisation of substrate and enzymes promoting the formation of melanin. The occurrence of cellular damage is dependent on the physical characteristics of the tuber such as turgor, fracture strain and stiffness. Turgor, dry matter concentration [DM] and the general water status of tubers are generally accepted as being of importance in determining the frequency of bruising but without sufficient understanding to allow preventative management. The aim of this project was to link all aspects of crop water use, crop water status, growing and harvesting conditions and soil water status in a study which should create the understanding to allow preventative management of the bruising risk.

The starting point for this project was to appreciate the changes which take place in tuber water and [DM] during growth and post-defoliation. During growth tubers accumulate DM and water in varying proportions but in broad terms [DM] increases over time and reaches a peak some 4-6 weeks before defoliation. Thereafter, [DM] may remain constant or change in either direction. Dry matter in tubers is principally starch and therefore the presence, number, size and angularity of starch grains may be important simply on the basis of their potential for physical damage to membranes when cells are deformed by impact. Cell wall thickness and elasticity may be unrelated to overall tuber [DM]. Tissue porosity, cell size, orientation and packing affect the way in which impact energy is dissipated through a tuber. All of these attributes appear to be affected by tuber (and therefore soil) water status but we have scarce knowledge of these as yet. Although the water content of tubers must also alter with changes in tuber [DM], this need not represent a change in turgidity of the tubers. Changes in either of these variables are not necessarily mediated through the other. For this reason, it is not surprising that convincing evidence that bruise susceptibility is directly related to tuber [DM] *per se* is very scarce, a view which will surprise many growers who strongly believe in this relationship. Any relationships between bruising and tuber [DM] are probably dependent on the manner in which a change in DM is achieved. Changing it via deliberate alteration of tuber water status (turgor) is a quite a different process from that achieved as a consequence of assimilate accumulation during normal growth.

Changes in tuber turgor, at any [DM], occur as a result of the movement of small amounts of water into or out of tubers over short time frames in response to changes in the water balance of the soil-plant system. During daylight, the tubers can provide a supply of water to the rest of the plant if uptake from soil is limited, thereby reducing their turgor which they recover towards the end of the night. For example, Stark & Halderson (1987) showed that tubers expanded towards the end of the night and in the early morning, which is the period associated with maximum turgor recovery (Kramer 1969). Shortly after sunrise, tubers begin to contract and reach a minimum circumference during the afternoon and evening hours. Their data show that a 50 mm diameter tuber could decrease by 0.762 mm during the day. Assuming no increase in loading of DM by day and ascribing the changes in diameter solely to a loss of water, the change in water content of the tubers would be *c*. 1.47 %. This is comparable to the magnitude of change that Bajema *et al*. (1998) found affected tissue toughness and failure stress. In reality, this figure of water loss is likely to be higher since some accumulation of starch would occur increasing the amount of DM in the tuber. Gandar & Tanner (1976) observed diurnal changes in tuber WP during a drying phase and the magnitude of diurnal changes in tuber WP, if converted to absolute quantities of water moving out of the tuber, are greater than those resulting in changes in tissue toughness, failure stress and failure strain which would influence bruising. The capacity of a tuber to supply water ("capacitance") is affected by prevailing soil conditions over considerable periods and after a prolonged period of drying, rehydration takes longer to occur than the dehydration (Gander & Tanner 1976). This is certainly important if growers are attempting to rehydrate tubers just prior to harvest to avoid bruising since roots die during crop senescence and defoliation and water uptake from the soil is therefore limited in many crops. There is an important point here: it is crucial to distinguish whether rehydration at this stage of the season is via water movement into the tuber across the periderm, or via internal movement of water from other plant organs or from active roots deeper in the soil profile that have access to water. C. Hole (personal communication) has shown that virtually no water movement into tubers occurs through the periderm of mature tubers immersed in water.

Irrigation post-defoliation is commonly practised in dry summers/autumns in the UK in order to reduce bruising but in many cases the role of irrigation is solely to ensure adequate soil retention on the primary web of harvesters so that tubers are cushioned and prevented from rolling backwards on the web. Therefore, is this instance, irrigation is applied immediately prior to harvest. The effect of post-defoliation irrigation on the hydration status of tubers and their bruising susceptibility several weeks later remains uncertain but in the BPC National Bruising Survey (BPC 2004; Fellows 2004), 33 % of growers recognised soil moisture at burn-off as having a major or very major influence on bruising. Furthermore, 38 % said they would consider irrigating just prior to burn-off to raise soil moisture levels in dry soils *if shown proof that it could make a real difference.* In dry soils, the application of small quantities of irrigation would merely wet the ridge profile and not reach any active roots deeper in the profile. This is important since rehydration of tubers could only arise from movement of water across the periderm in such circumstances, whereas if water were to reach living roots in the subsoil re-hydration could take place by movement of water internally within the plant. The state of activity of the rooting system and the extent of water movement throughout the soil following irrigation would crucially affect re-hydration. Finney & Findlen (1967) found that pruning the roots significantly lowered the elasticity of tissue (turgor pressure) within the tubers in both irrigated and unirrigated plots. In the absence of haulm and roots any significant re-hydration must arise from direct movement across the periderm.

In an experimental context, Bajema *et al*. (1998) demonstrated that tuber turgor altered susceptibility to bruising. They dehydrated stored tubers by placing them at different temperatures and relative humidities for 3½ to 7 days to induce a weight loss of 0-1.5, 1.5-3, 3-4.5 and > 4.5 %. As turgor decreased (from 0-1.5 % to 1.5-3.0 % weight loss) failure strain and tissue toughness increased markedly and failure stress increased slightly. There were larger effects observed in Russet Burbank than in Atlantic. As weight loss increased beyond 3 % (i.e. turgor decrease), failure strain increased slightly but failure stress and tissue toughness decreased. There seemed to be an optimal hydration status for tissue toughness and bruise threshold but this was less than full turgor. Thus, there is direct evidence linking turgor with the physical characteristics which determine susceptibility as suggested by Smittle *et al*. (1974). However, there are no quantitative results which relate changes in turgor to changes in the susceptibility of tubers to bruising in specific soil and environmental conditions. The principal reasons for this are a) the difficulty in obtaining rapid measurement of turgor and b) the concomitant consequence of ignoring it and concentrating on changes in [DM], which are not the same.

The project aimed to a) quantify the relationships between expression of bruising and tuber turgor and b) establish the relationships between tuber turgor and soil water status so that growers can be given clear guidance as to the management practices which will minimize bruise susceptibility and allow corrective management of tubers identified as susceptible. This guidance is centred on management of soil water status and the timing of defoliation and harvesting. A series of linked experiments used treatments generating a wide range of plant and soil water potentials. It was important to first establish systems for measuring tuber turgor with sufficient frequency to establish its relation to soil water status, secondly quantify the linkage between bruising and tuber turgor and thirdly establish the agronomic conditions which are likely to result in tubers with the least risk of bruising.

Material and methods

Experiments

There were six experiments conducted during the course of the study.

Experiment 1 (2004)

This experiment was designed to test the effects of a) wet soil with no canopy and active roots, b) wet soil with an active canopy but limited root length and c) detaching tubers hydraulically from both roots and foliage in dry and wet soil on tuber water potential and bruising. The experiment was a randomised split-plot design with irrigation treatments as main plots and varieties, defoliation and root-cutting treatments allocated at random to sub-plots within the main plots. Treatments were allocated at random within three replicate blocks. Treatments were all combinations of the following:

1. Two varieties known to have high [DM] and believed to have different susceptibilities to internal damage: Lady Rosetta; Smith's Comet.
2. Two irrigation regimes: rain fed only (Unirrigated); irrigated to maintain soil moisture deficit (SMD) ≤ 20 mm (Irrigated). Irrigation was continued until final harvest on Defoliated and Cut treatments as for Undefoliated, Uncut irrigated plots. The dates and amounts of irrigation applied are listed in Table 1.
3. Two haulm defoliation treatments: left to senesce naturally (Undefoliated); defoliated mechanically using a hedge-trimmer at on 3 August 80 days after emergence (Defoliated).
4. Two root cutting treatments: roots left to senesce naturally (Uncut); roots undercut at base and sides of ridge at 80 days after emergence using a powered hacksaw (Cut).

TABLE 1. IRRIGATION TIMING AND AMOUNTS (MM) FROM EMERGENCE UNTIL FINAL HARVEST IN EXPT 1

	Irrigation regime	
Date	Unirrigated	Irrigated
4 June		16.6
10 June		19.7
15 June		24.8
21 June		24.2
29 June		26.5
5 July		23.1
22 July		23.4
28 July		23.4
3 August		23.0
12 August		20.8
18 August		18.0
Total irrigation	0	244
Rain	177	177
Drainage[†]	0	79

[†] Average Lady Rosetta and Smith's Comet

Experiment 2 (2005)

This experiment widened the varietal diversity and aimed to test the effect of withholding water around the onset of crop senescence. The experiment was a randomised split-plot design with irrigation treatments as main-plots and varieties randomised as sub-plots within main-plots, with three replicates. Treatments were all combinations of the following:

1. Three varieties: Lady Rosetta; Maris Piper; Smith's Comet. The two crisping types have high [DM] and different susceptibilities to physical damage and blackspot bruising whilst Maris Piper is the most widely-grown UK variety.
2. Four irrigation regimes: rain fed (Unirrigated); irrigated with *c.* 20 mm to maintain SMD ≤ 25 mm (Irrigated); irrigated at same time as Irrigated except for 3 weeks without rain and irrigation starting 15 July (Pre-dry); irrigated at same time as Irrigated except for 3 weeks without rain and irrigation starting 5 August (Post-dry). Pre- and Post-dry treatments were protected from rainfall during the restricted periods with rain shelters. Irrigation amount was initially reduced to 15 mm whilst re-wetting Pre- and Post-dry irrigation treatments. The dates and amounts of irrigation applied are listed in Table 2.

TABLE 2. IRRIGATION TIMING AND AMOUNTS (MM) FROM EMERGENCE TO FINAL HARVEST IN EXPT 2

	Irrigation treatment			
Date	Unirrigated	Irrigated	Pre-dry	Post-dry
7 June		16.9	16.9	16.9
10 June		18.3	18.3	18.3
17 June		20.1	20.1	20.1
21 June		19.1	19.1	19.1
24 June		19.9	19.9	19.9
15 July		14.0		14.0
18 July		15.2		15.2
22 July		13.6		13.6
1 August		13.2		13.2
5 August		13.7	13.7	
9 August		14.4	14.4	
12 August		15.0	15.0	
26 August			20.8	20.8
2 September		24.1	24.1	24.1
Total irrigation	0	218	182	195
Rain	286	286	267	237
Drainage†	28	125	107	80

†Mean of all three varieties

Experiment 3 (2006)

Experiment 3 was conducted with Lady Rosetta. Treatments were a factorial combination of the following, fully randomized within three replicate blocks:

1. Four irrigation regimes: rain fed (Unirrigated); irrigated with *c*. 20-24 mm to maintain SMD ≤ 25 mm (Irrigated); irrigated at same time as Irrigated except for 2 weeks without rain and irrigation starting 15 July to allow a 60 mm SMD to accumulate (Pre-dry); irrigated at same time as Irrigated except for 17 days without rain and irrigation starting 1 August, (Post-dry). The weather was dull during the Post-dry period and the SMD only reached 43 mm rather than the target 60 mm. Irrigation applications are detailed in Table 3.
2. Three haulm defoliation regimes: left to senesce naturally (Undefoliated); mechanically defoliated using a hedge trimmer and shears at end of Pre-dry period (Defoliated Pre-dry); defoliated at end of Post-dry period (Defoliated Post-dry).

TABLE 3. IRRIGATION TIMING AND AMOUNTS (MM) FROM CROP EMERGENCE IN EXPT 3

	Irrigation treatment			
Date	Unirrigated	Irrigated	Pre-dry	Post-dry
8 June		21.4	21.4	21.4
13 June		20.0	20.0	20.0
23 June		21.9	21.9	21.9
27 June		21.7	21.7	21.7
3 July		21.7	21.7	21.7
10 July		21.7	21.7	21.7
17 July		24.1		24.1
20 July		24.0		24.0
25 July		24.2		24.2
31 July		20.5	20.5	20.5
4 August		21.8	21.8	
11 August		19.2	19.2	
Total irrigation	0	262	190	221
Rain	192	192	174	158
Drainage†	2	95	38	38

†From emergence until final harvest

Experiment 4 (2006)

This experiment used Maris Piper and treatments were all combinations of the following:

1. Two cultivation regimes: cultivated whilst soil was dry (Cult Dry); cultivated whilst soil was wet (Cult Wet).
2. Two irrigation regimes: rain fed (Unirrigated); irrigated with *c*. 20-25 mm to maintain the SMD ≤ 30 mm (Irrigated). Irrigation was applied as detailed in Table 4.
3. Four nitrogen fertilizer application amounts: 0; 100; 200; 300 kg N/ha.

TABLE 4. IRRIGATION TIMING AND AMOUNTS (MM) FROM EMERGENCE TO FINAL HARVEST IN EXPT 4

	Irrigation regime	
Date	Unirrigated	Irrigated
10 June		19.9
24 June		26.3
29 June		18.7
5 July		20.1
14 July		22.3
18 July		24.5
24 July		25.1
7 August		25.6
Total irrigation	0	183
Rain	222	222
Drainage[†]	3	30

[†] Mean of Cult Dry and Cult Wet

The experimental design was a randomised split-plot with irrigation x cultivation treatments as main plots and nitrogen fertilizer treatments as sub-plots, with three replicate blocks. The cultivation treatments were imposed as follows. Ridges were initially drawn up using a Rumpstad Rotoridger bed-tiller on 27 March. These were knocked down on 5 April by spring-tining at a shallow depth. The Cult Wet plots were irrigated with 18 mm on 6 April at 15:00 h and left to dry for 18 hours. The Rumpstad Rotoridger was then used to draw up ridges again on the whole experiment. Very uneven ridges were made in the Cult Wet plots so on 18 April, these were power-harrowed, avoiding the compacted layer created by the bed-tiller by cultivating only 15 cm deep. The Cult Wet plots were then re-ridged using a fixed-body Cousins ridger but the Cult Dry plots were also re-ridged at the same time to avoid any further confounding of treatments.

Experiment 5 (2007)

Treatments were a fully randomized factorial combination of the following, with four replicate blocks:

1. Four irrigation regimes: rain fed (Unirrigated); irrigated with *c*. 17-21 mm to maintain SMD ≤ 25 mm (Irrigated); irrigated at same time as Irrigated except for 3 weeks without rain and irrigation starting 13 July to allow a 53 mm SMD to accumulate (Pre-dry); irrigated at same time as Irrigated but no rainfall or irrigation after 3 August (Post-dry). Total irrigation applied was considerably less than in previous seasons and is detailed in Table 5.
2. Two defoliation regimes: Undefoliated; mechanically defoliated using shears on 3 August on completion of the Pre-dry period (Defoliated).

TABLE 5. IRRIGATION TIMING AND AMOUNTS (MM) FROM EMERGENCE UNTIL FINAL HARVEST IN EXPT 5

	Irrigation treatment			
Date	Unirrigated	Irrigated	Pre-dry	Post-dry
8 June		16.9	16.9	16.9
14 June		19.1	19.1	19.1
10 July		20.9	20.9	20.9
30 July		17.1		17.1
7 August		17.1	17.1	
16 August		19.2	19.2	
Total irrigation	0	110	93	74
Rain	320	320	293	265
Drainage	71	132	112	92

Experiment 6 (2007)

This experiment used Maris Piper and treatments were all combinations of the following:

1. Two cultivation regimes: cultivated whilst soil was dry (Cult Dry); cultivated whilst soil was wet (Cult Wet).
2. Two irrigation regimes: rain fed (Unirrigated); irrigated with *c.* 20-25 mm to maintain the SMD ≤ 30 mm (Irrigated). Irrigation is detailed in Table 6.
3. Three nitrogen fertilizer application amounts: 0; 150; 300 kg N/ha.

TABLE 6. IRRIGATION TIMING AND AMOUNTS (MM) FROM EMERGENCE TO FINAL HARVEST IN EXPT 6

	Irrigation regime	
Date	Unirrigated	Irrigated
25 April†		19.0
2 May†		24.4
11 June		24.6
10 July		19.1
17 July		18.5
2 August		20.7
9 August		24.8
5 September		18.8
13 September		20.8
Total irrigation	0	147
Rain	261	261
Drainage	53	102

†Post-planting, pre-emergence irrigations

The experimental design was a randomised split-plot with irrigation x cultivation treatments as main plots and nitrogen fertilizer treatments as sub-plots, with four replicate blocks. The cultivation treatments were imposed as follows. Ploughed land was spring-tined twice on 26 March at 10-15 cm depth. The Cult Wet plots were irrigated with 18.8 mm on 19 April between 16:00 and 20:00 h and left to dry for 21 hours. A Rumpstad Rotoridger was then used to cultivate the whole experiment. Ridges were then drawn up using a fixed-body Cousins ridger.

General

Throughout the experiments, seed tubers (35-45 mm in Expts 1, 2, 3 and 5, 35-40 mm in Expt 4 and 30-35 mm in Expt 6) were hand-planted at a spacing of 0.25 m using dibbers into pre-formed ridges of width 0.76 m. The dates of planting were: Expt 1, 15 April; Expt 2, 11 April; Expt 3, 4 April; Expt 4, 19 April; Expt 5, 5 April; Expt 6, 23 April. Nitrogen fertilizer (180 kg N/ha) was applied as liquid pre-emergence except where different levels of nitrogen fertilizer treatments were imposed. In these cases, ammonium nitrate prills were spread by hand over the top of the ridges immediately post-planting. No other fertilizer was used as soil indices were high in all experiments.

In Expts 1-3 and 5, plots were 6 m long, comprising of four harvest rows protected by one guard row either side. Two additional planted guard rows either side of each plot prevented water moving laterally between plots and the furrows at the end of each plot were tie-bunded to prevent water ingress from adjacent plots. Rain covers for Pre- and Post-dry treatments were the same dimensions as the plots (6 x 4.5 m) and the polythene was only drawn across the frames when rain was actually falling or imminently forecast. In Expts 4 and 6, plots were four rows wide by 10 m in length.

Overhead irrigation was applied through a boom (RST Irrigation) and hose reel (Perrot SA, SH63/280) combination. Mean irrigation amounts were estimated from 12 rain gauges per irrigation treatment, situated at ground level and not shielded by foliage. 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 ET equation. Reference crop evapotranspiration (ET_0) was calculated using the parameters of Allen *et al.* (1998) for a grass reference crop. The potato irrigation model takes account of changing leaf area index, stomatal conductance and canopy surface roughness on the demand side and root growth and Limiting SMD based on soil water tension and rooting depth on the supply side. Meteorological data were collected using an electronic logger (Delta-T Devices Ltd) attached to an anemometer (Vector Instruments), a screened, combined relative humidity sensor and air temperature thermistor (Skye Instruments Ltd) and a pyranometer measuring total incident global radiation (Kipp & Zonen BV) all located at 2 m height on a mast situated within the experimental field area. The ratio of actual : potential SMD was determined by the current SMD and the daily ET_0 rate (Stalham & Allen 2004).

Crop emergence was recorded by counting plants in two central harvest rows every 2-3 days. Ground cover was estimated weekly using a grid (Burstall & Harris 1983) at the same position in the plot. In Expts 1, 3 and 5, all foliage from defoliated crops was removed from plots, with any re-growth of stems being cut back with secateurs.

Tuber [DM] was determined by chipping *c.* 500-600 g of washed tubers into an aluminium food tray, weighing accurately, drying in a fan-assisted oven at 90° C for 48 hours using 90 % recirculated air and reweighing.

Final harvests for all experiments were taken in mid to late September and comprised of 12 plants from guarded harvest rows (10 plants in Expts 4 and 6). Separate samples were harvested for bruising to avoid any risk of damage during grading. The number and weight of tubers in 10 mm grades was measured.

Variates were analysed by analysis of variance using the GenStat Release 6.1 statistical package (Payne *et al*. 2002). 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. In Expts 4 and 6, not all of the nitrogen treatments were sampled for bruising and WP measurements but the levels used are stated.

Water potential (WP)

Measurement of tuber WP, a good estimate of turgor (Gandar & Tanner 1976), was made using a Skye Instruments SKPM1400 pressure chamber. At intermediate harvests, four to six guarded plants per plot were dug carefully by hand from harvest rows in the field so that tubers remained attached to their stolons. Unless there were frequent measurements of WP and bruising during the day, tubers for WP and impact testing were harvested between 08:00 and 10:00 h. Tubers for WP 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 WP but could be used for bruising or [DM] assessment. At least ten tubers with intact stolons were removed from the plants by cutting the stolon as close to the stem as possible using scissors and carefully packed in sealed plastic bags for transport to the laboratory. All other harvested tubers > 40 mm were placed carefully into paper sacks for bruising or [DM] tests. The tubers with stolons were washed and allowed to dry before trimming the end of the stolon with a perpendicular cut using a scalpel. The cut stolon was carefully inserted through the aperture of the rubber sealing washer. A selection of sealing washers was available to suit the size of the stolons. These were slit to allow insertion of the stolon without bending or breakage. The sealing washer was then pushed into the low pressure head of the pressure bomb and screwed onto the chamber. The stolon protruding from the pressure head was trimmed to a length suitable for viewing easily using a magnifying glass and the cut surface blotted dried using paper towel. The chamber was pressurized using compressed air at a slow rate until a film of sap was just visible on the cut surface of the stolon and the pressure noted. The chamber was depressurized, the stolon end dried and the measurement repeated twice more (three readings per tuber). A total of five tubers per plot were measured for WP.

Leaf WP was measured in the same way as tuber WP. The 6th leaf > 5 mm length below the uppermost leaf was cut through the petiole at the stem junction using a scalpel and placed in a sealed ziplock bag. Five leaves per plot were sampled, one each from five individual guarded plants. Leaf WP samples were harvested and transported to the laboratory one replicate block at a time and measured as quickly as possible. Samples were kept at 4 °C between sampling and measuring to minimize loss of turgor. Only two replicate measurements were made per leaf to ensure rapid processing of samples.

Relative water content

Relative water content (RWC) is the weight of water present in tissue before incubation in pure (distilled) water, relative to that present after incubation in pure water. It is normally assumed that tissue incubated in water will reach full turgor, so RWC gives an indication of the turgidity of the tissue. However, there is a tendency for tissue to start decomposing after prolonged incubation at room temperature, so shorter incubation times are frequently used.

In Expt 6, 10 tubers per plot were harvested, taken to the laboratory, washed carefully, dried using tissue paper and a plug of tissue 10 mm in diameter taken from the stolon end of the tuber using a cork borer. The position of the plug was intended to mimic the likely impact site of the falling bolt impactor. Using tweezers to handle the plug, a cut was made with a sharp scalpel to remove a 1 mm thick slice of tissue to exclude periderm tissue. The tissue plug was then trimmed to a length of 10 mm by making a perpendicular cut at the opposite end of the plug. The plug was blotted dry on tissue paper by touching each cut end once on the paper and rolling backwards and forwards around the circumference to ensure dryness. The plug was then weighed to ± 0.001 g and dropped into a clean sample bottle containing 10 ml of distilled water at 25 °C and the time noted. After the incubation period, plugs were removed with tweezers, shaken and then blotted dry as before and then re-weighed. Relative water content (%) was calculated as 100*((final weight − initial weight)/initial weight).

An initial response curve of weight gain versus time was created by incubating plugs for different periods of time and re-weighing. Assuming that no further gain in weight would occur after 24 h incubation, it was found that 6 h incubation produced 95 % of the full response and 3 h, 90 %. In order to fit in with the number of samples being measured, incubation had to be restricted to 90 minutes at 25 °C, which only produced 70 % of the full response but gave significant differences in RWC of tubers grown under contrasting irrigation regimes.

Impact bruising

At the same time as WP was being determined, 25 (Expts 1-4) or 50 tubers/plot (Expts 5-6) were subjected to a falling bolt damage test on the stolon end using 0.5 J of energy (equivalent to a *c*. 300 mm drop height for a 60 mm tuber). The impact was made using a steel coach bolt of 182.6 g mass which had a domed head of diameter 22 mm with a radius of curvature at the impact site of 150 mm. This was dropped from a height of 279 mm (0.5 J) inside an aluminium guide tube of 40 mm internal diameter onto the stolon end of the tuber. The tuber was positioned on its apical end and prevented from falling over by the bottom of the guide tube. The guide tube was held by a pair of retort stand clamps, one acting as a guide, the other clamping the tube at the correct height above the tuber. The impacting surface was an 18 mm thick x 200 x 150 mm steel baseplate supported on a 30 mm thick MDF work surface. Different energy levels (0.3-2.0 J) were used on occasion to test the effect of higher impact energy on damage type and severity. The energy levels were varied by using guide tubes of different lengths. It was decided to use a higher energy of 1.0 J for Maris Piper in Expt 4 since little blackspot bruising was observed in this variety in Expt 2 using 0.5 J energy.

All WP and impact tests were carried out at 20-22 °C except in the temperature variation studies. Once tubers had been impacted, they were placed in trays and left at 25 °C for 48 hours before damage assessment. A single peel (depth *c*. 1.5-1.6 mm) was removed at the site of impact using an Oxo Good Grips Swivel Peeler and then a further five peeler strokes were made to detect deeper damage or until the damage was removed. The depth of the bruise was the number of peeler strokes required to remove the damage completely multiplied by the thickness of peel removed by the peeler. Calibrations were performed on the peel thickness every alternate harvest during each season by measuring 100 random peel slices with a Mitutoyo Thickness Gage. Two peelers were alternated during the season to ensure even wearing of the blades and two new peelers were used each season. The type of damage was noted as cellular leakage (white, chalky, Brie-rind type discolouration), external cracking or blackspot bruising with black, blue or grey hue. The maximum width and breadth of blackspot bruises were measured and volume calculated from the depth estimated from peeling.

Impact energy and temperature studies

On two occasions in Expt 1 (20 July and 6 September), four impact energy levels (0.5, 1.0, 1.5 and 2.0 J) were used on a common treatment (Lady Rosetta, Irrigated, Undefoliated, Uncut). Fifty random tubers from each plot were used for each energy level. In Expt 2, four energy levels (0.5, 1.0, 1.5 and 2.0 J) were tested on 22 August and 9 September. Tubers from the Irrigated treatments of all varieties were used, with 50 tubers per plot being impacted at each energy level.

In Expt 2, 250 tubers from the Post-dry plots were harvested on 19 September. These tubers were allocated to five 50-tuber batches at random. Each batch was equilibrated at a different temperature (2, 8, 12, 15, 25 °C) for 8 hours before impacting. In Expt 5, tubers were harvested from the Pre-dry Defoliated treatment on 12 September, with 50 tubers from each replicate allocated at random to three temperature (4, 8, 20 °C) and three energy (0.3, 0.4, 0.5 J) levels and stored at 8 °C until 8 November when tubers were moved to the relevant temperature storage for 8 hours. Tubers were then impacted using the respective energy level and scored 48 hours later.

Drying studies

In Expt 1, on three occasions (27 July, 13 August, 21 September), 10 tubers from all Uncut plots were placed under controlled conditions of constant temperature and ventilation which caused them to lose water vapour and therefore turgor. The temperature was kept at *c*. 25 ºC and air flow over the tubers maintained using a 350 mm desk fan. On the first two occasions, the fan was run at its highest speed and caused moderate to severe dehydration. At the last of the three drying events, no forced ventilation was used and drying was therefore slower.

Comparison of different bruising impactors

Tests were conducted in Expt 2 to compare three different impactor tools and their effect on tuber damage levels and type of damage. These tools were: CUF falling bolt (detailed in materials and methods), nominal energy at impact 0.5 J; Durham University School of Biological & Biomedical Sciences ‘bruise gun’, which used a compressed spring to accelerate an impactor head to a nominal energy of 0.8 J; Scottish Agricultural College (SAC) pendulum impactor, delivering a nominal energy of 0.4 J at impact.

On two occasions (12 August and 2 September), 600 tubers (> 35 mm) were dug carefully from discard rows of Irrigated plots. These were selected randomly and placed stolon end uppermost in 25-tuber batches in cardboard egg trays and allocated at random to the treatments: three impactors, two temperatures at impact (8 and 25 °C) and four replicates (100 tubers per treatment). One half of the trays were placed at 8 °C for 8 hours and the other half were placed at 25 °C. The tubers were then impacted using the different tools at the two temperatures. All tubers were then placed at 25 °C for 48 h before assessing the damage.

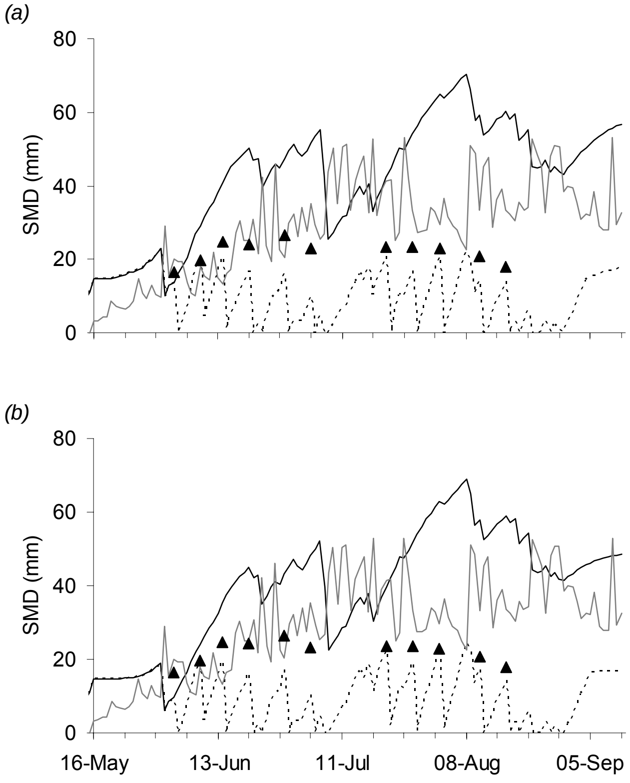
4. Results

Soil moisture deficits

Experiment 1

Radiation and rainfall receipts between emergence and final harvest were both slightly higher than average but ET_0 was appreciably higher than the long-term average at CUF. This meant that there were prolonged periods in June and again in late July and August when Unirrigated crops had SMDs well above the Limiting SMD (Figure 1). Maximum SMD in both varieties reached *c.* 70 mm in rain fed plots but timely irrigation in Irrigated plots prevented the SMD exceeding 24 mm, with the mean SMD being maintained < 10 mm. A large differential in SMD (*c.* 35 mm) between the two irrigation treatments was maintained throughout the harvesting phase.

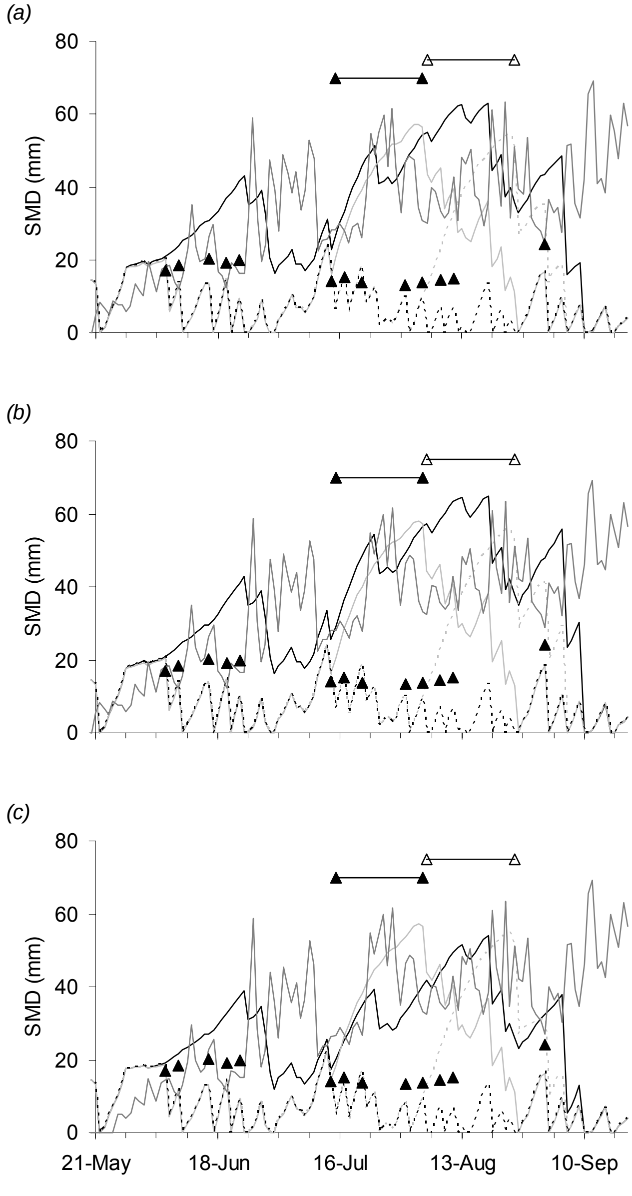
Figure 1. Modelled soil moisture deficits (SMD) in *(a)* Lady Rosetta; *(b)* Smith's Comet
Unirrigated —; Irrigated ----; Limiting —; irrigation, ▲.



Experiment 2

Despite reference crop evapotranspiration (ET_0) being slightly above average during June-August 2005, a considerably duller July reduced the ET_0 in the middle of the season. Soil moisture deficits increased rapidly in the Unirrigated crops during June, but the low ET_0, combined with considerable rain at the end of June and in the middle of July prevented substantial SMDs being attained until the third week of July (Figure 2). For the majority of August, SMDs were maintained at 50-70 mm in Unirrigated treatments before 80 mm of rain in early September removed any deficit. As a consequence, all plots were within 10 mm of field capacity at final harvest. The Irrigated treatments were maintained below the target of 25 mm SMD for the entire season. The Pre-dry plots rapidly increased their SMD on being deprived of water in mid-July for three weeks, reaching the same, or higher, maximum SMD as Unirrigated plots. Re-watering Pre-dry plots after the drought period gradually brought the SMD back to the level of the Irrigated plots by the end of August. The Post-dry treatments reached slightly lower maximum SMDs than the Pre-dry plots since the ET_0 rates were lower in August (2.9 mm/day) than when the drought treatments were imposed on the Pre-dry plots (3.2 mm/day) but, more importantly, the ground cover decreased rapidly in Lady Rosetta and Smith's Comet during the Post-dry treatment period. A considerable variation in soil water status was therefore achieved between the irrigation treatments, both in magnitude and timing.

Figure 2. Modelled soil moisture deficits in *(a)* Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet
Unirrigated —; Irrigated ----; Pre-dry —; Post-dry ----; Limiting, —; irrigation (Irrigated treatment), ▲; stress periods, Pre-dry, ▲—▲; Post-dry, △—△.

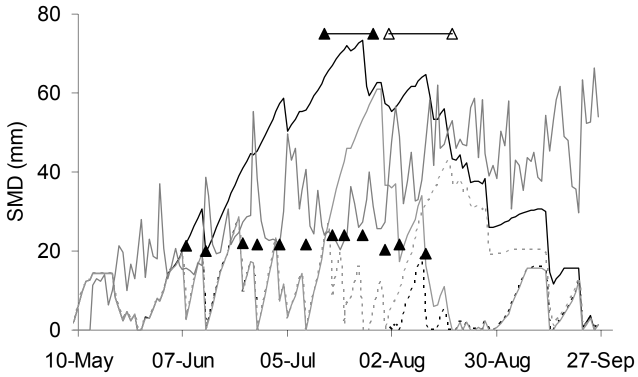


Experiment 3

2006 was a hot summer with radiation receipts in June and July being *c.* 20 % above average but August was 15 % duller than average. Reference ET_0 was consequently greater in June and July than long-term averages, with a mean daily ET_0 of 4.04 mm/day *c.f.* only 2.43 mm/day in August. There was an 11-day period starting mid-July when temperatures reached a maximum of over 30 °C each day and where ET_0 attained a peak of 6.0 mm but generally ET_0 was lower than typical for the temperatures since windruns were small and relative humidity's high which restricted ET_0. August was slightly wetter than average but coupled with the low ET_0 demand meant that SMDs generally fell in all plots that were not protected by rain covers.

Soil moisture deficits reached *c.* 70 mm in Unirrigated plots and 60 mm at the end of the stress period in Pre-dry treatments, thereby maintaining the soil substantially drier than that needed to maintain the potential ET (Figure 3). Evaporative demand during the Post-Dry period was low and SMDs only reached 43 mm by the end of the period with modelled SMD maintained below the Limiting SMD. Soil moisture deficit was maintained below 27 mm in Irrigated plots and less than the Limiting SMD to ensure free access to soil water.

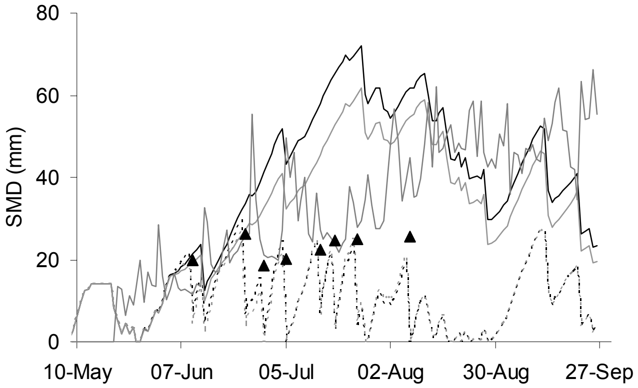
Figure 3. Modelled soil moisture deficits (SMD) in Expt 3 (undefoliated treatments only)
Unirrigated, —; Irrigated, ----; Pre-dry, —; Post-dry, ----; Limiting, —; irrigation (Irrigated treatment), ▲; stress periods, Pre-dry, ▲—▲; Post-dry, △—△.



Experiment 4

In Unirrigated plots, SMDs were lower in the Cult Wet treatments than the Cult Dry as a consequence of the smaller canopies and the reduced uptake potential based on a smaller rooting system (Figure 4). The SMD exceeded the Limiting SMD for the whole of July. There were only small differences in SMD between irrigated treatments but soils were kept wet throughout the season (< 30 mm SMD) and therefore below the Limiting SMD.

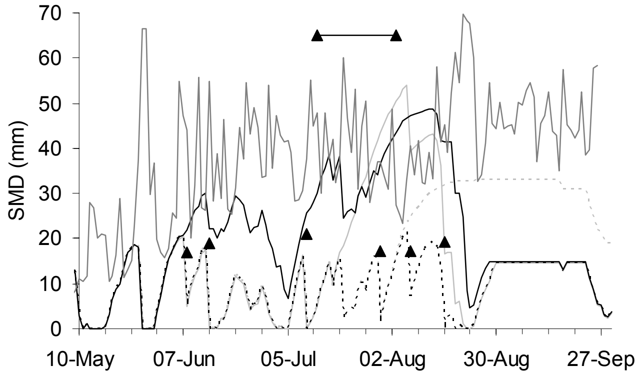
FIGURE 4. MODELLED SOIL MOISTURE DEFICITS (SMD) IN EXPT 4 (MEAN N100-N300 TREATMENTS ONLY)
Cult Dry, Unirrigated, —; Cult Dry, Irrigated,----; Cult Wet, Unirrigated, —; Cult Wet, Irrigated, ----; irrigation, ▲; Limiting SMD, —.



Experiment 5

The season was characterized by a particularly dull, cold May, followed by a slightly duller than average June, July and August. Evaporative demand was *c.* 6 % lower than average during the growing season and there was 30 mm more rainfall in June-August than the average of 157 mm. At the end of May, 62 mm fell in two days which refilled all soils. Consequently, the season did not permit the generation of very high SMDs, despite the use of covers. Soil moisture deficits reached *c.* 49 mm in Unirrigated plots (20 mm less than in previous years) and 53 mm at the end of the stress period in Pre-dry treatments (Figure 5). Soil moisture deficit was maintained below 22 mm in Irrigated plots and less than the Limiting SMD which ensured free access to soil water.

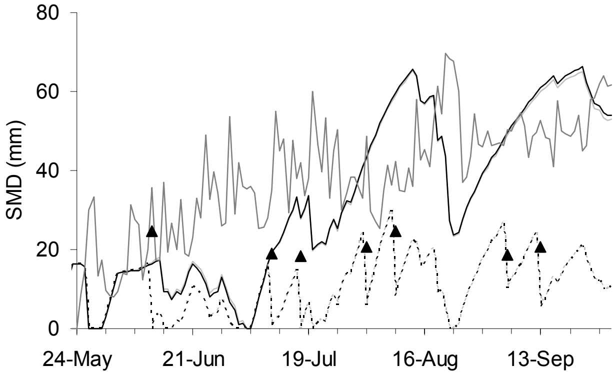
FIGURE 5. MODELLED SOIL MOISTURE DEFICITS (SMD) IN EXPT 5 (UNDEFOLIATED TREATMENTS ONLY)
Unirrigated, —; Irrigated, ----; Pre-dry, —; Post-dry, ----; Limiting, —; irrigation (Irrigated treatment), ▲; Pre-dry stress period, ▲—▲.



Experiment 6

Soil moisture deficits in the Unirrigated crops only exceeded the Limiting SMD for a two-week period starting at the beginning of August and for the final two weeks of growth but there was sufficient shortage of water during these periods for irrigation to affect productivity more than in Expt 4 (see p. **Error! Bookmark not defined.**). Soil moisture deficits in Irrigated crops were maintained below 27 mm throughout the season (Figure 6).

FIGURE 6. MODELLED SOIL MOISTURE DEFICITS (SMD) IN EXPT 6 (MEAN N150 AND N300 TREATMENTS ONLY)
Cult Dry, Unirrigated, —; Cult Dry, Irrigated,----; Cult Wet, Unirrigated, —; Cult Wet, Irrigated, ----; irrigation, ▲; Limiting SMD, —.

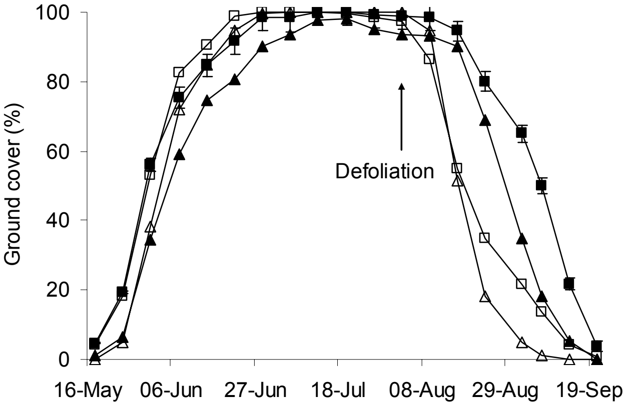


Ground cover (GC)

Experiment 1

The GC of Smith's Comet was affected by soil water shortage sooner after emergence than Lady Rosetta and Unirrigated crops did not attain complete GC whereas Lady Rosetta did (Figure 7). Whilst irrigation advanced early GC, it also hastened senescence appreciably so that total GC duration (i.e. seasonal light interception capacity) was decreased considerably in Irrigated *c.f.* Unirrigated crops.

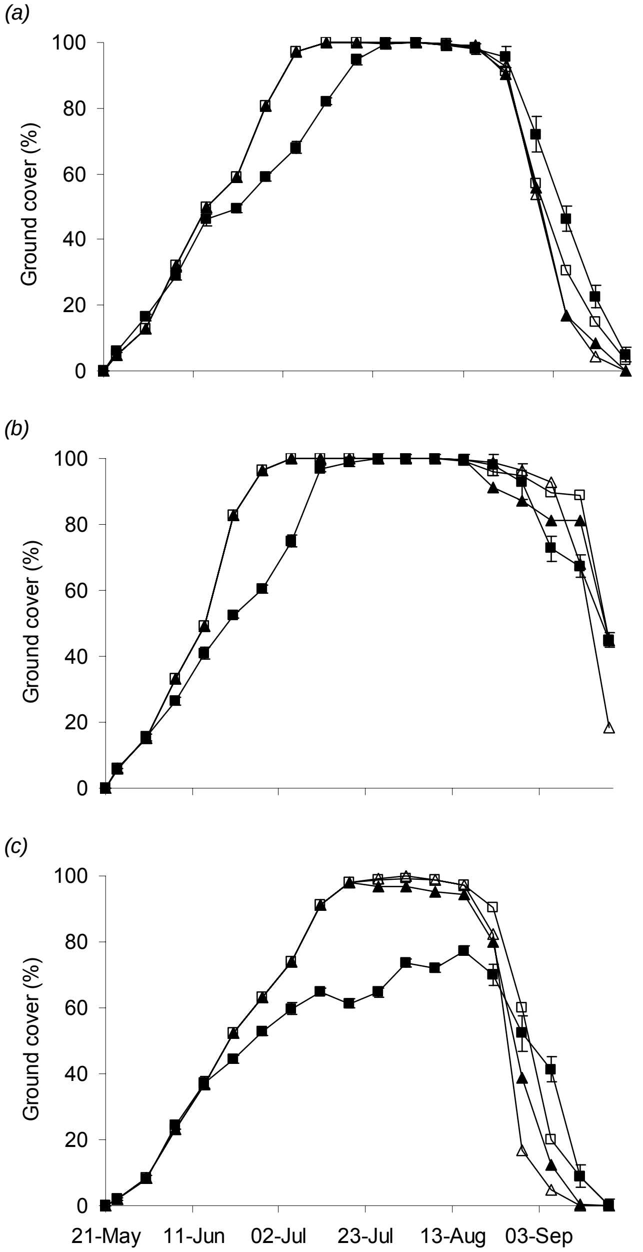
FIGURE 7. GROUND COVER IN EXPT 1
Lady Rosetta Unirrigated, ■; Lady Rosetta Irrigated, □; Smith's Comet Unirrigated, ▲; Smith's Comet Irrigated, △. S.E. based on 28 D.F.



Experiment 2

Rate of increase in GC was reduced in all varieties by withholding water from the beginning of the season (Figure 8). Full GC was not reached in Unirrigated Smith's Comet. All other plots reached full GC but Unirrigated plots took three weeks longer to reach it than treatments receiving irrigation. Withholding water temporarily for three weeks from the beginning of August (Post-dry treatment) caused a rapid loss in leaf area in all varieties.

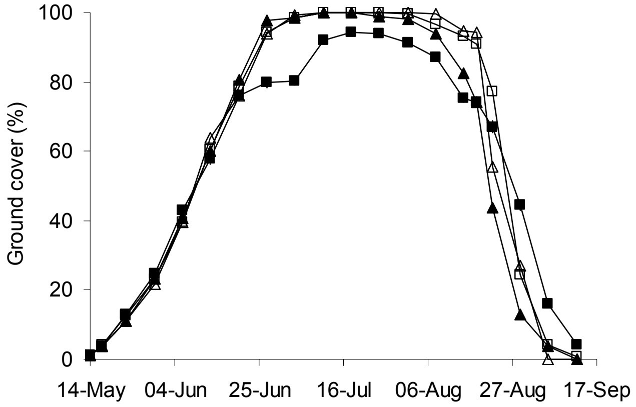
Figure 8. Ground cover in Expt 2. *(a)* Lady Rosetta; *(b)* Maris Piper*; (c)* Smith's Comet
Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 16 D.F.



Experiment 3

Rate of increase in GC was unaffected by withholding water from the beginning of the season until *c*. 80 % GC had been achieved (Figure 9). The Unirrigated crops survived the high temperatures and almost complete absence of rainfall in the first two week of June without suffering any loss of GC development but started to slow in leaf area development at *c*. 37 mm SMD. Unirrigated crops did not reach full GC and started senescing at the same time as the Irrigated treatments. However, as observed in several previous experiments in Lady Rosetta, the rate of decrease in GC was slower in Unirrigated crops than in crops which had received irrigation. The water supply in Pre-dry treatments was restricted at the start of the prolonged hot spell in the second half of July and the soil rapidly accumulated a considerable SMD (61 mm). Ground covers remained completely closed during the restricted period but by mid-August, Pre-dry treatments began to senesce at a more rapid rate than other treatments. The Post-dry irrigation restriction had no effect on GC since the evaporative demand was lower during the restricted period than during the Pre-dry period and the maximum SMD attained was only 43 mm.

FIGURE 9. GROUND COVER IN EXPT 3 (UNDEFOLIATED TREATMENTS ONLY)
Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 22 D.F.

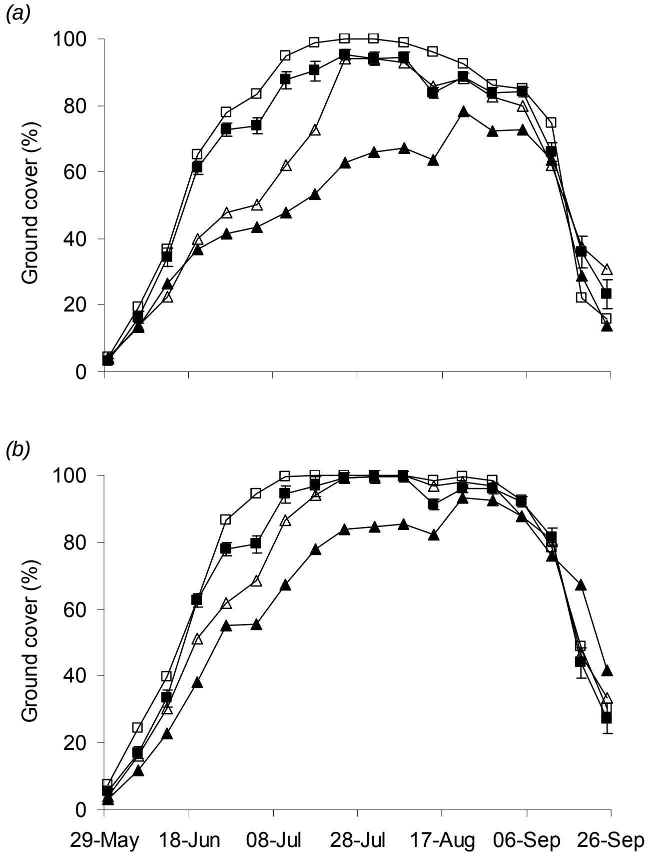


Experiment 4

Initial rate of increase in GC was reduced by cultivating the soil whilst wet and the canopies only reached a maximum of 80 % GC if unirrigated (Figure 10). There was a two-day delay in emergence of Cult Wet treatments compared with Cult Dry but only a small part of the difference can be attributed to this short delay. Since the crops grown in compacted soil commenced senescence at the same time at those grown in loose soil, there was a large decrease in GC duration (i.e. radiation absorption capacity) of Cult Wet crops compared with Cult Dry. Irrigation increased both the rate of canopy cover and maximum GC significantly in Cult Wet plots and to a smaller extent in Cult Dry crops. Growing crops in uncompacted soil without irrigation produced crops with greater potential radiation capture than those grown in compacted soil with irrigation. Adding 300 kg N/ha increased the rate of canopy development and the duration of maximal GC and the response was larger in crops grown in compacted soil but complete GC was still not achieved.

Figure 10. Ground cover in Expt 4

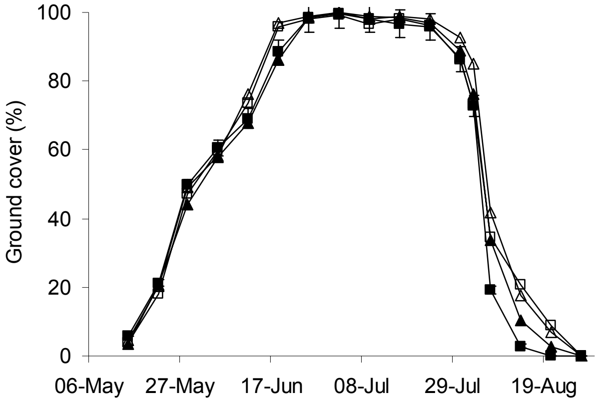
(a) 0; *(b)* 300 kg N/ha. Cult Dry, Unirrigated, ■; Cult Dry, Irrigated, □; Cult Wet, Unirrigated, ▲; Cult Wet, Irrigated, △. S.E. based on 24 D.F.



Experiment 5

The season was characterized by a cool, dull May which slowed the rate of increase in GC of all crops. There was a small delay in reaching full GC in Unirrigated crops *c.f.* Irrigated but otherwise little difference was evident between irrigation treatments until the onset of senescence (Figure 11). Senescence was very rapid compared with previous seasons and crops experiencing drought stress during the season (Unirrigated, Pre-dry) senesced more rapidly than fully-irrigated crops.

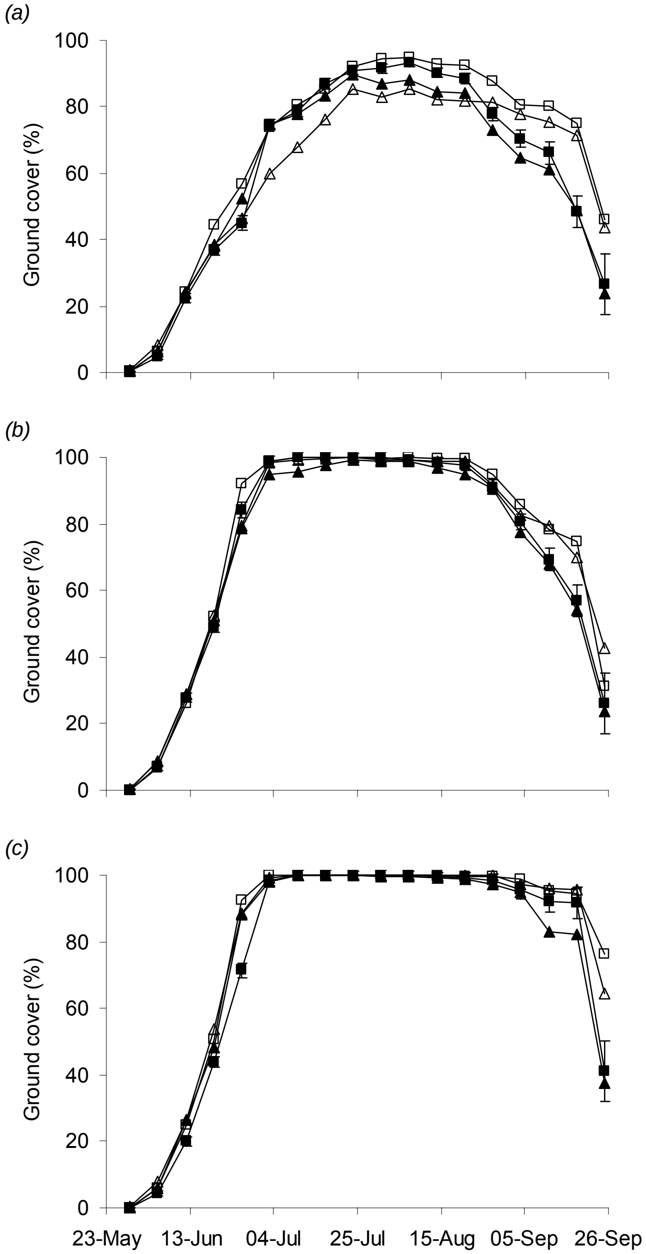
FIGURE 11. GROUND COVER IN EXPT 5 (UNDEFOLIATED TREATMENTS ONLY)
. Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 21 D.F.



Experiment 6

The effects of soil cultivations, irrigation and nitrogen application rate on GC are shown in Figure 12. In the absence of nitrogen fertilizer, initial GC expansion was slow and crops failed to achieve complete GC. When 150 (data not shown) or 300 kg N/ha was applied, GC expansion was rapid and all crops attained 100 % GC. When 300 kg N/ha had been applied, canopy senescence was delayed by 2-3 weeks when compared with the intermediate nitrogen rate (data not shown). In all cases irrigation increased canopy persistence but in the Cultivated Wet and unfertilized crop, irrigation early in the season reduced ground cover. The effects of cultivating the soils whilst wet or dry on GC development and persistence were smaller than the effects of either irrigation or nitrogen application rate.

FIGURE 12. GROUND COVER IN EXPT 6. *(A)* 0; *(B)* 150 *(C)* 300 KG N/HA
Cult Dry, Unirrigated, ■; Cult Dry, Irrigated, □; Cult Wet, Unirrigated, ▲; Cult Wet, Irrigated, △. S.E. based on 24 D.F.



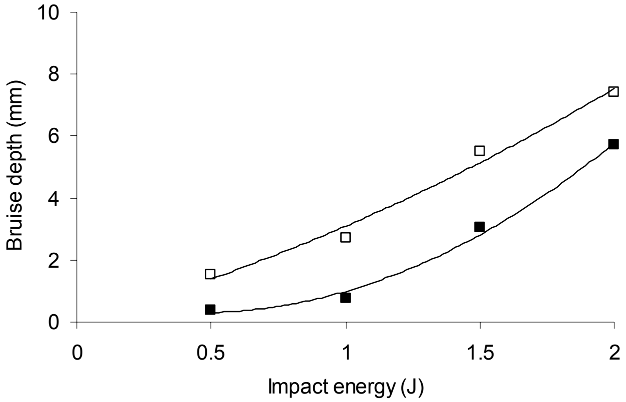
Bruising

Effect of energy of impact

Experiment 1

On 20 July, there was a small increase in bruise depth by increasing energy from 0.5 to 1.0 J, a large increase from 1.0 to 1.5 J and an even larger change from 1.5 to 2.0 J (Figure 13). The same trend in increasing bruise severity with increasing energy was observed for 6 September (Figure 13) but the increment between 1.5 and 2.0 J was not proportionally as large as the earlier harvest and the bruising severity at any given energy was higher in September than in July. There was a significantly better degree of fit when using quadratic relationships rather than linear.

FIGURE 13. EFFECT OF IMPACT ENERGY ON DEPTH OF BRUISING ON TWO OCCASIONS (LADY ROSETTA, IRRIGATED, UNDEFOLIATED, UNCUT) IN EXPT 1.
20 July (■); 6 September (□). Relationships: 20 July, $y = 2.28x^2 - 2.05x + 0.76$, $R^2 = 0.99$; 6 September $y = 0.697x^2 + 2.35x + 0.05$, $R^2 = 0.98$.



Experiment 2

As energy level increased, internal damage and blackspot increased but there were different responses depending on when the tubers were tested during the season. On 22 August, all varieties had a similar response in bruising to increasing energy (Figures 14*a* and 15*a*). However, later in the season, Maris Piper had a much lower response in bruise depth than Lady Rosetta and Smith's Comet as energy increased. In terms of blackspot incidence, Lady Rosetta had more blackspot bruising on 9 September as energy level increased than either Maris Piper or Smith's Comet. For some relationships, there were significantly better degrees of fit when using quadratic or exponential relationships rather than linear.

FIGURE 14. EFFECT OF IMPACT ENERGY ON BRUISE DEPTH ON TWO OCCASIONS IN EXPT 2
(a) 22 August, *(b)* 9 September. Relationships using mean values: *(a)* Lady Rosetta, ■, $y = 1.029e^{1.034x}$, $R^2 = 0.99$; Maris Piper, □, $y = 0.443e^{1.439x}$, $R^2 = 0.97$; Smith's Comet, ▲, $y = 0.968e^{1.063x}$, $R^2 = 0.98$; *(b)* Lady Rosetta, ■, $y = 4.386x+1.48$, $R^2 = 0.97$; Maris Piper, □, $y = 3.768x-0.19$, $R^2 = 0.94$; Smith's Comet, ▲, $y = 5.119x-0.12$, $R^2 = 0.99$. S.E. based on 8 D.F.

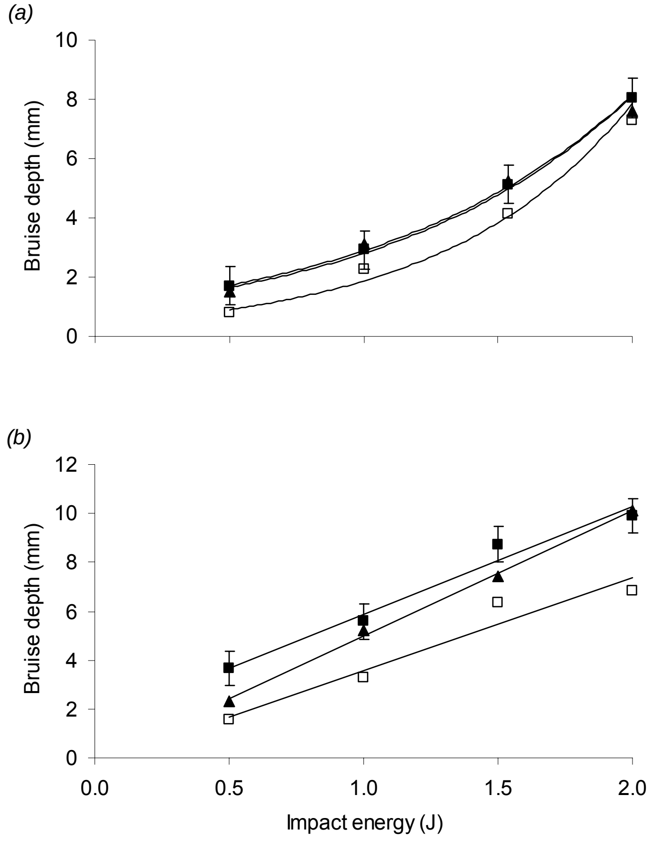
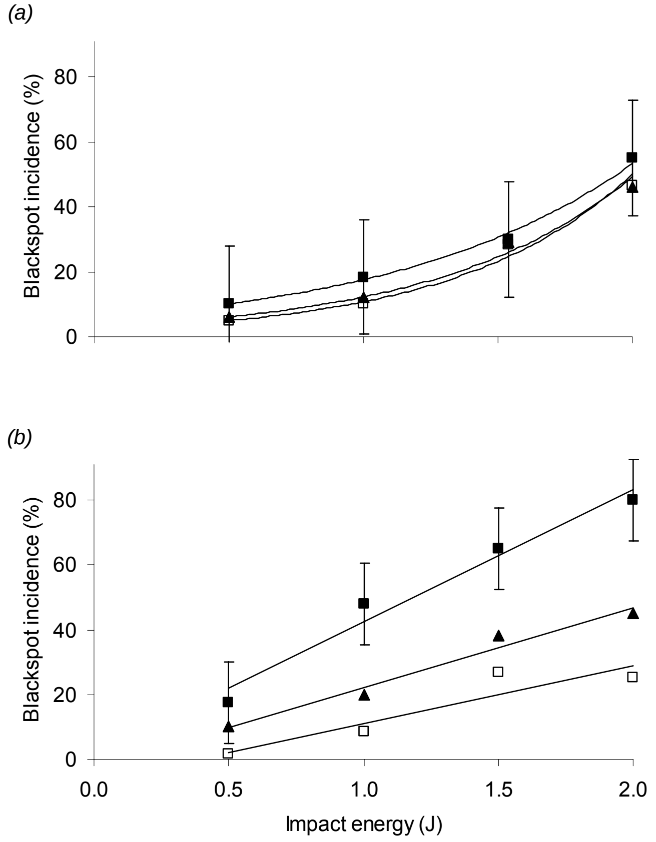


Figure 15. Effect of impact energy on blackspot bruise incidence on two occasions in Expt 2
(a) 22 August, *(b)* 9 September. Relationships using mean values: *(a)* Lady Rosetta, ■, $y = 5.789e^{1.110x}$, $R^2 = 0.99$; Maris Piper, □, $y = 2.302e^{1.541x}$, $R^2 = 0.99$; Smith's Comet, ▲, $y = 3.0511e^{1.391x}$, $R^2 = 0.99$; *(b)* Lady Rosetta, ■, $y = 40.90x+1.50$, $R^2 = 0.97$; Maris Piper, □, $y = 17.78x−6.76$, $R^2 = 0.86$; Smith's Comet, ▲, $y = 24.67x−2.50$, $R^2 = 0.97$. S.E. based on 8 D.F.

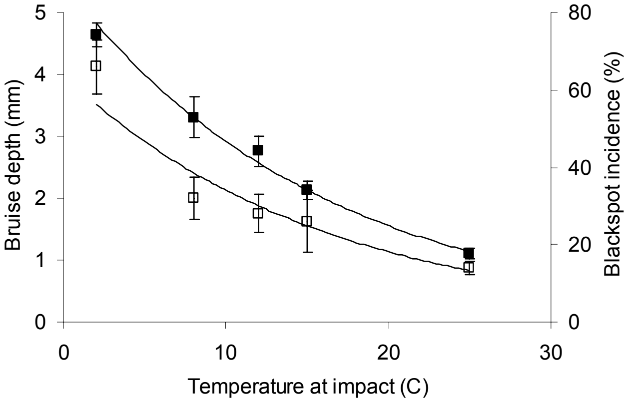


Effect of temperature at bruising

Experiment 2

The effect of tuber temperature at impact on blackspot incidence and bruising severity was examined in Post-dry tubers harvested on 19 September. Both blackspot incidence and bruise depth increased rapidly as the temperature of the tuber decreased below 8 °C, especially the incidence of blackspot (Figure16).

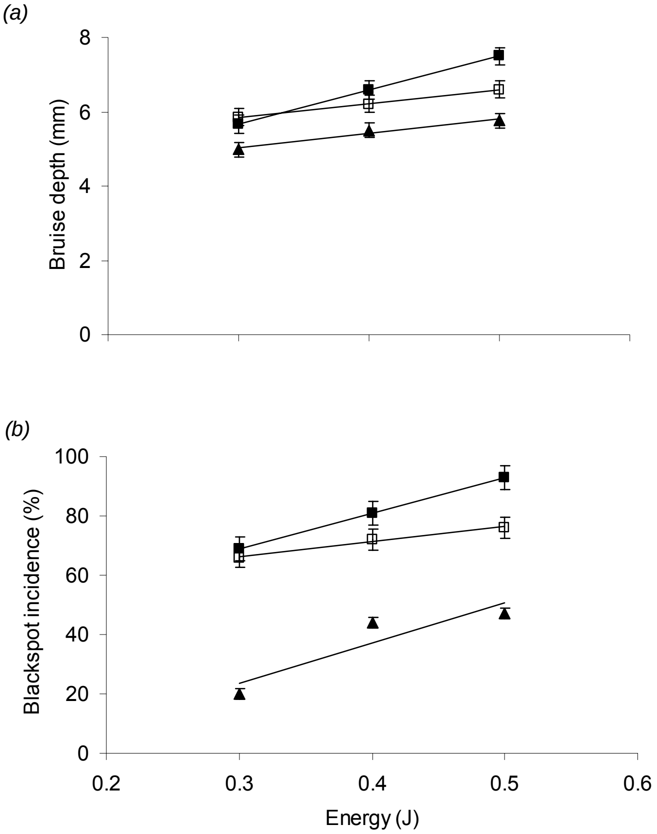
FIGURE16. EFFECT OF TUBER TEMPERATURE AT IMPACT ON BRUISE DEPTH AND BLACKSPOT INCIDENCE IN EXPT 2 Relationships using mean values: bruise depth, ■, $y = 5.468e^{-0.0629x}$, $R^2 = 0.99$; blackspot, □, $y = 63.84e^{-0.0629x}$, $R^2 = 0.94$. S.E. based on 10 D.F.



Experiment 5

The incremental increases in energy were smaller and the lowest energy smaller than in previous tests. At 4 °C, the increase in bruise depth with increasing energy was greater than at higher temperatures (Figure 17*a*). When examining blackspot incidence, temperature had a much greater effect than on bruise depth. There was a much lower incidence at 20 °C than at 4 or 8 °C and the response to increasing energy from 0.3 to 0.5 J was similar at 4 and 20 °C (Figure 17*b*).

Figure 17. Effect of temperature and impact energy on *(a)* bruise depth; *(b)* blackspot incidence in Expt 5, Pre-dry Defoliated treatment only.
Relationships *(a)*: 4 °C, ■, $y = 9.13x+2.93$, $R^2 = 0.99$; 8 °C, □, $y = 3.75x+4.71$, $R^2 = 0.99$; 20 °C, ▲, $y = 3.92x+3.84$, $R^2 = 0.96$; *(b)* 4 °C, ■, $y = 120x+33$, $R^2 = 0.99$; 8 °C, □, $y = 50x+51$, $R^2 = 0.98$; 20 °C, ▲, $y = 135x-17$, $R^2 = 0.83$. S.E. based on 24 D.F.



The conclusion of these series of studies on temperature and energy is that it is crucial to standardize both temperature and energy when impacting tubers for bruise assessment. An impact energy of 0.5 J in Lady Rosetta and Smith's Comet produced an acceptable range of bruising for detecting differences between treatments but Maris Piper bruised less using such an energy. It was clear that impacts occurring at temperature of 8 °C and lower resulted in much more severe bruising than in the range 12-20 °C.

Comparison of different bruising impactors

Experiment 2

On 12 August, the CUF and Durham impactors had similar incidences of internal damage, blackspot bruising and damage severity at 8 °C but the Durham tool produced less bruising at 25 °C than the CUF impactor (Table 7). The SAC tool produced less bruising than the other two impactors, especially at 25 °C. On 2 September, the incidence of blackspot had decreased considerably, even at 8 °C, however there was a high incidence of internal damage. The CUF tool used at 8 °C resulted in nearly all (90 %) tubers showing damage (Table 8). The Durham and SAC tools produced the similar results at the same temperature. On 12 August, the Durham and SAC impactors caused external cracking in 4 % of tubers bruised at 8 °C, whereas there was no cracking using the CUF tool. However, on 2 September, there was 26 % cracking using the CUF tool at 8 °C whereas there was only 4 % cracking incidence using the Durham and SAC tools. In summary, it appears that the CUF falling bolt impactor generally produced the most severe damage, with the SAC impactor the least. The movement of the Durham impactor from being more similar to the CUF tool on 12 August to the same as the SAC tool (i.e. lower) on 2 September clearly warrants further investigation if it is to be used as an industry 'standard'.

TABLE 7. EFFECT OF IMPACTOR TYPE ON DAMAGE INCIDENCE AND SEVERITY ON 12 AUGUST IN EXPT 2

		Damage type			
Tool	Impact temperature (°C)	Internal damage incidence (%)	Blackspot incidence (%)	Cracking incidence (%)	Bruise depth (mm)
CUF	8	80	40	0	3.31
	25	68	6	0	1.98
Durham	8	82	32	4	3.19
	25	52	18	0	1.06
SAC	8	74	8	4	2.93
	25	30	2	0	0.80
	S.E. (15 D.F.)	4.9	6.0	1.3	0.262

TABLE 8. EFFECT OF IMPACTOR TYPE ON DAMAGE INCIDENCE AND SEVERITY ON 2 SEPTEMBER IN EXPT 2

		Damage type			
Tool	Impact temperature (°C)	Internal damage incidence (%)	Blackspot incidence (%)	Cracking incidence (%)	Bruise depth (mm)
CUF	8	90	4	26	4.56
	25	46	0	0	1.75
Durham	8	58	2	2	2.28
	25	24	0	0	0.65
SAC	8	60	0	4	2.74
	25	26	0	2	0.72
	S.E. (15 D.F.)	9.4	1.2	3.1	0.390

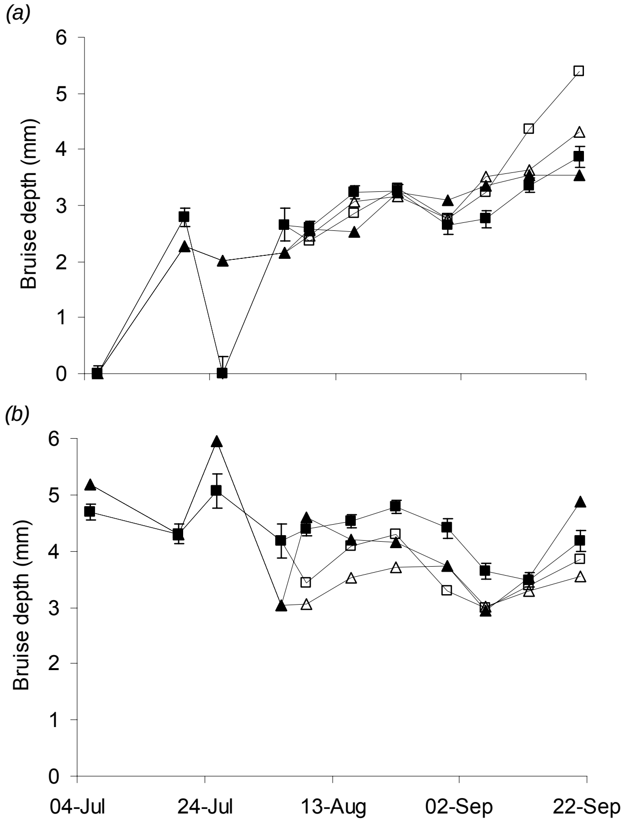
Timecourse of bruising

Experiment 1

There was considerable splitting or cracking of tubers in Smith's Comet early in the season when tubers were hydrated. There was virtually no shatter cracking or splitting in Lady Rosetta, even early in the season and with impact energies of up to 1.5 J. Using an impact energy of 0.5 J, the typical grey/black discolouration associated with classical blackspot bruising did not appear until 16 August. Instead, bruises were mostly a chalky white in texture and colour, which was presumably caused by a leakage of cell contents but without involving polyphenol oxidase reactions with tyrosine from rupture or leakage of internal membranes within the cell. Blackspot bruising increased progressively from 2.1 % incidence on 16 August to 39.2 % on 21 September in Lady Rosetta and from 2.9 % to 8.3 % in Smith's Comet over the same period. Overall severity of bruising, as measured by depth of damage, increased gradually in Lady Rosetta during early season, stabilized during August and then increased significantly between successive harvests during September (Figure 18). In Smith's Comet, the high incidence of shatter cracking during July decreased during August but blackspot bruising increased throughout September as in Lady Rosetta but at a much slower rate. This general increase in bruising during September was interesting since [DM] was stable during this period and WP reasonably stable also (see later).

FIGURE 18. BRUISING SEVERITY (DEPTH OF BRUISE) IN EXPT 1

(a) Lady Rosetta; *(b)* Smith's Comet. Unirrigated, Undefoliated, ■; Unirrigated, Defoliated, □; Irrigated, Undefoliated, ▲; Irrigated, Defoliated, △. Mean of Uncut and Cut treatments. S.E. based on 4-28 D.F.



In Lady Rosetta, the magnitude and direction of changes in bruising severity prior to 23 August could not be used to predict bruising severity at the end of the season. For example, Unirrigated, Undefoliated crops had the highest bruise severity on 9 August but were significantly the lowest in early September, whereas Unirrigated, Defoliated Lady Rosetta had the lowest bruise score on 9 August but showed the most rapid increase during September so that it was the most bruise susceptible treatment at final harvest. In contrast, in Smith's Comet, the Unirrigated, Undefoliated crops generally had significantly worse bruising than other treatments throughout most of the season.

The effect of defoliation on bruising was interesting. In Unirrigated Lady Rosetta defoliated mechanically during a period of high ET_0 and when the SMD was high exhibited a more rapid increase in bruising post-defoliation than crops left to senesce naturally (Figure 18). The difference in blackspot incidence became progressively worse and was highly significant at final harvest (30 ± 7.8 % and 67 % for Undefoliated and Defoliated, respectively). There was no significant difference between defoliation regimes in bruising at final harvest in Irrigated crops. Clearly, there was a change in physical properties of tubers from crops defoliated when experiencing severe water stress.

Experiment 2

Similar to Expt 1, there was considerable splitting or cracking of tubers in Smith's Comet early in the season when tubers were hydrated. The cracks mostly originated at the apical end of the tuber or occasionally from the middle section of the tuber rather than the impacted end. There was virtually no shatter cracking or splitting in Lady Rosetta, even early in the season and with impact energies of up to 2.0 J. In Maris Piper, tubers with pointed stolon ends showed symptoms of crushing on impact as opposed to cracking at the apical end which occurred with Smith's Comet. Using the standard impact energy of 0.5 J, the typical grey/black discolouration associated with classical blackspot bruising did not appear until 30 August, two weeks later than in Expt 1. Instead, bruises were mostly "whitespot", although a brown melanin-type compound was often associated with moderate-severe internal damage in Smith's Comet early in the season. This should not be confused with blackspot bruising since later in the season it was possible to observe both browning and blackspot reactions in damaged areas of tissue in Smith's Comet.

In Lady Rosetta, the incidence and severity of internal damage was lowest when impact testing commenced (mid-July) and rose to a peak for all treatments at the end of August (Figures 19*a* and 20*a*). When mean damage scores were most severe, it took an average of 4.2 mm of peeling to remove the damage from affected tubers. Internal damage was confined to whitespot bruising early in the season but when bruising was at its most severe it included a significant proportion (33 %) of blackspot bruising (Figure 21*a*). Internal damage incidence decreased during September and blackspot incidence followed a similar trend, with the exception of the Pre-dry treatment which increased from a low point in early September. In contrast, in Expt 1 blackspot bruising increased throughout September but the maximum incidence was similar between seasons, albeit occurring earlier in Expt 2 than in Expt 1. Throughout the season, internal damage was generally greatest for Unirrigated crops with the exception of an aberration on 5 September (Figure 19*a*). Internal damage incidence and severity rose during the drought stress period in the Pre-dry treatment but following irrigation, damage decreased and remained lower than other irrigation treatments until final harvest. At final harvest, the two treatments with temporary water stress imposed on them had lower damage and blackspot incidence than either Unirrigated or Irrigated plots.

In Maris Piper, internal damage was much more superficial than in Lady Rosetta, with the damage being confined to an average depth of 3.1 mm beneath the periderm. Whilst there were significant differences in damage incidence on occasions throughout the season (Figure 19*b*), there were no significant differences between irrigation treatments in damage severity in Maris Piper (Figure 20*b*), nor in blackspot incidence which was < 8% when using 0.5 J impact energy (Figure 21*b*).

In Smith's Comet, internal damage was high at the start of impact testing (over 85 % incidence, Figure 19*c*) as was the incidence of external cracking, with over 40 % of tubers cracking in Irrigated treatments (Figure 22*b*). Tubers often had internal cracks spreading from the impact site (as opposed to external cracks on the opposite end to the impact site) which could often be 3-4 mm deep below the periderm. These internal cracks were still evident even as external cracking decreased and they were usually associated with brown melanin-type discolouration around the impact site as opposed to blackspot (at energies higher than 0.5 J, blackspot and brown discolouration could be seen in different sections of the bruise but the blackspot was always confined to one area of the bruise and not intermingled with other areas of discolouration). Unirrigated crops had a lower incidence of cracking throughout the season than Irrigated. Where crops had water stress imposed for three weeks prior to the onset of senescence (Pre-dry), cracking decreased during the drought and then increased following rehydration of the soil in the three weeks following the end of the drought period. With the Post-dry treatment, cracking decreased following removal of irrigation compared with Irrigated crops and remained at a lower level until the beginning of September when all treatments had a lower incidence of cracking. Once blackspot started appearing, its incidence was higher in Post-dry treatments than in other irrigation treatments. Interestingly, during rehydration of the Post-dry treatments, cracking decreased to zero and blackspot increased. Despite the variation in internal damage during the season, by the final harvest in September, all treatments were similar (Figure 19*c*). External cracking, however, was higher in Irrigated crops than in other treatments for most of the season and was still significantly higher at final harvest (Figure 22*b*).

FIGURE 19. INTERNAL DAMAGE INCIDENCE IN EXPT 2
(a) Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet. Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 8-16 D.F. N.B. Different scales for Smith's Comet.

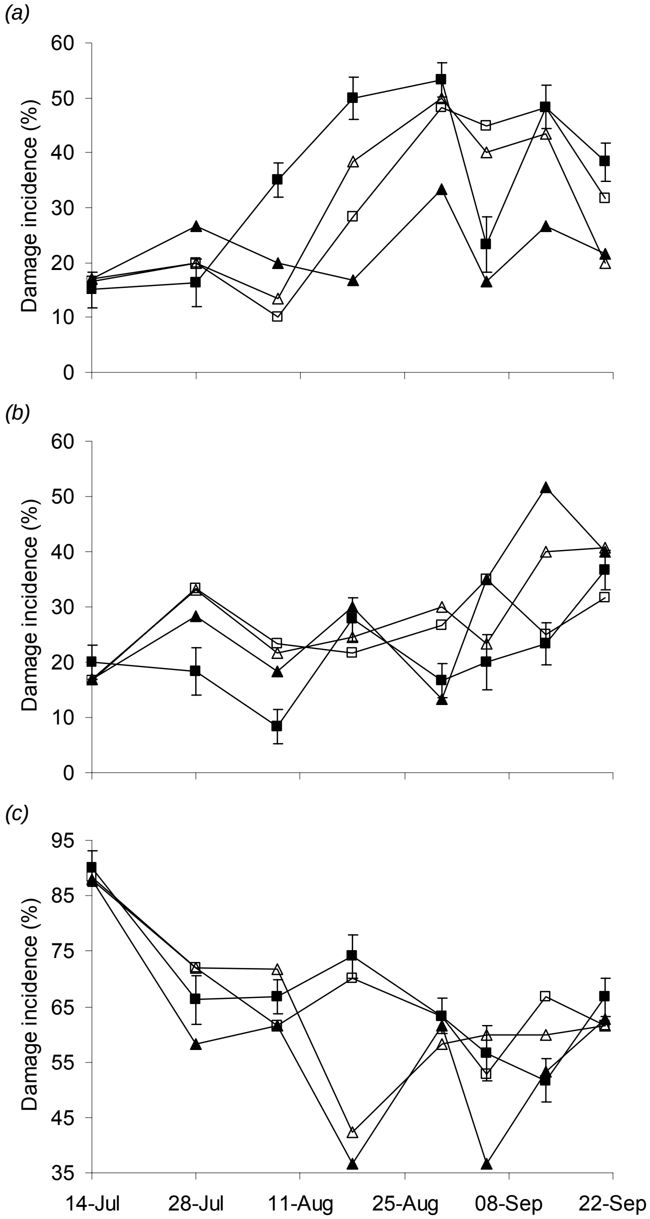


FIGURE 20. INTERNAL DAMAGE SEVERITY (BRUISE DEPTH) IN EXPT 2
(a) Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet. Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 8-16 D.F.

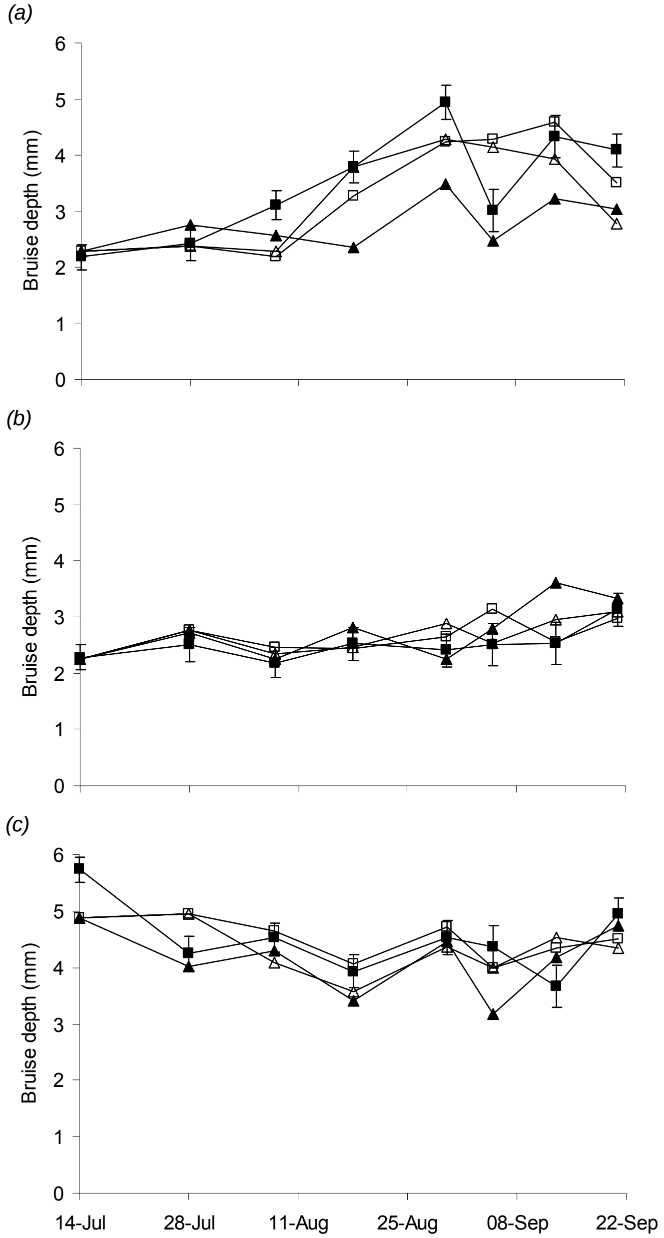


FIGURE 21. BLACKSPOT INCIDENCE IN EXPT 2
(a) Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet. Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 8-16 D.F.

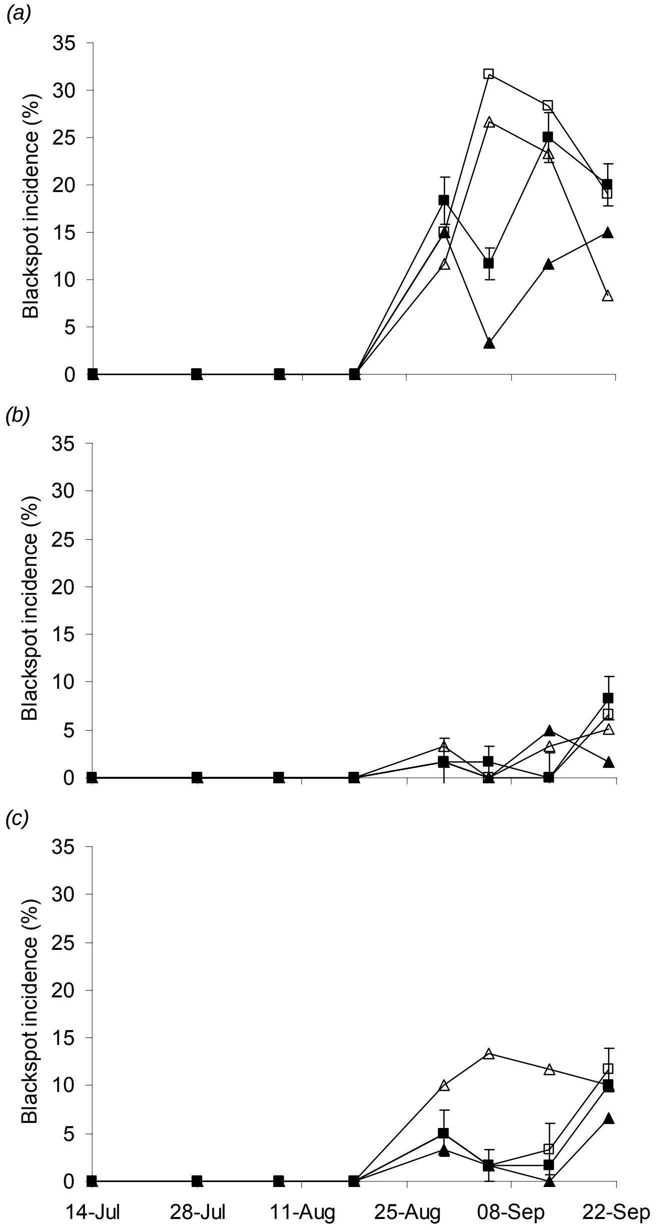
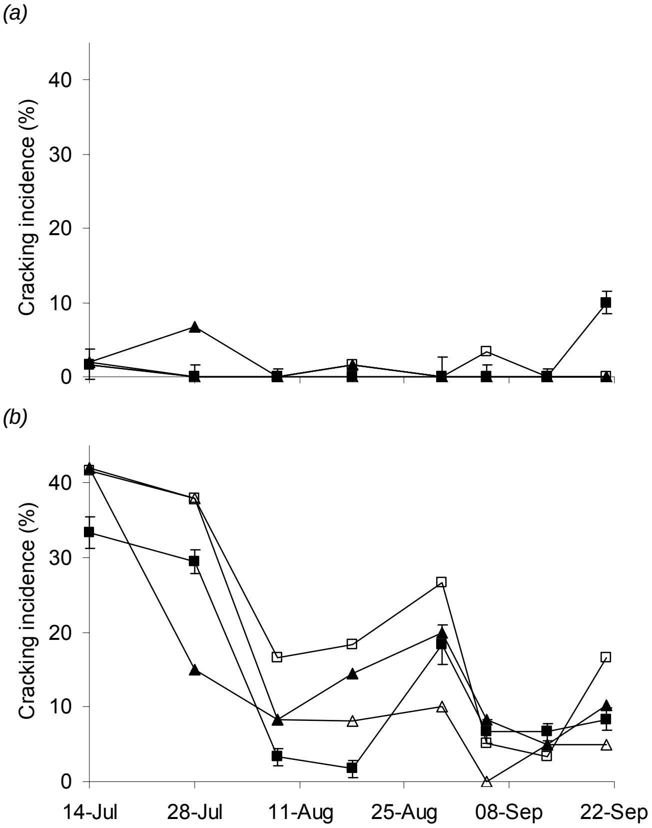


FIGURE 22. CRACKING INCIDENCE IN EXPT 2

(a) Maris Piper; *(b)* Smith's Comet. Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. Data not shown for Lady Rosetta as zero cracking observed. S.E. based on 8-16 D.F.



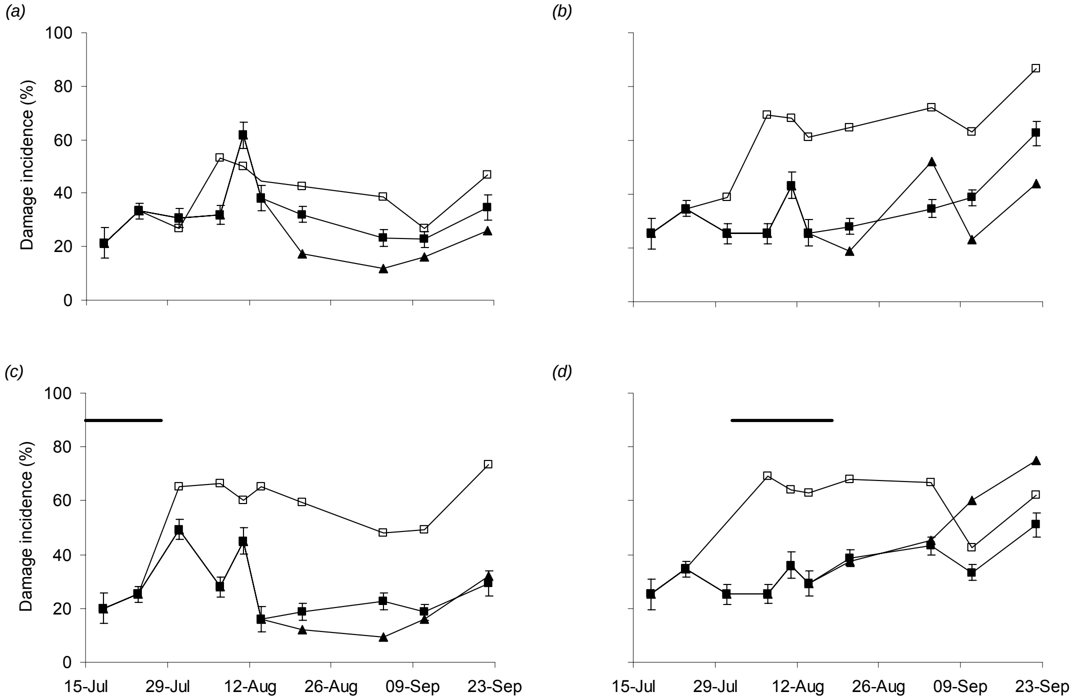
Experiment 3

The energy used (0.5 J) did not cause any external cracking. Impact bruising commenced in mid-July when internal damage was almost completely whitespot bruising (Figure 23). Blackspot bruising started to appear during the third week of July (Figure 24) compared with mid-late August in Expts 1 and 2 for crops which all emerged over the period 14-20 May each year. Maybe as a consequence of the earlier blackspot bruising, whitespot bruising was much less prevalent in Expt 3 than in the two previous seasons. Despite different watering regimes, bruising was largely similar across all treatments up to 18 July.

Blackspot bruising in all Irrigated and Post-dry crops increased slightly or remained constant during August whereas crops deprived of irrigation earlier in the season (Unirrigated or Pre-dry) slightly decreased from a peak in early August (Figure 24). Between 11 and 22 September blackspot bruising increased in all treatments so that the worst bruising was seen at final harvest towards the end of September, irrespective of the watering regime during the season (Figure 24; Table 9). Bruises became more severe (deeper) in susceptible tubers across all treatments as well increasing in incidence (Figure 25).

FIGURE 23. INTERNAL DAMAGE INCIDENCE IN EXPT 3

(a) Unirrigated; *(b)* Irrigated; *(c)* Pre-dry; *(d)* Post-dry. Undefoliated, ■; Defoliated Pre-dry, □; Defoliated Post-dry, ▲. Bar marks period of water restriction in Pre- and Post-dry irrigation treatments. S.E. based on 22 D.F.



Almost immediately after defoliation at the end of the Pre-dry stress period, there was a large increase in bruising, which subsequently remained higher than in crops which were not defoliated or defoliated after the Post-dry stress period, despite irrigation being applied to these crops after defoliation (Figures 23-25). The effects were greatest in the Irrigated and Pre-dry crops that were irrigated prior to the Pre-dry stress period and smaller but still mostly significant in the Unirrigated crops. The effect was not transitory since there were still large differences between Pre-dry defoliated crops and Undefoliated in Irrigated and Pre-dry crops at final harvest in September (Table 9). There was an obvious effect on the subsequent time course of bruising caused by mechanical defoliation of the crop. Crops defoliated after the Post-dry stress period also had increased blackspot bruising compared with Undefoliated crops (Figure 24*d*) but the effect was not as great as the earlier defoliation.

FIGURE 24. BLACKSPOT INCIDENCE IN EXPT 3

(a) Unirrigated; *(b)* Irrigated; *(c)* Pre-dry; *(d)* Post-dry. Undefoliated, ■; Defoliated Pre-dry, □; Defoliated Post-dry, ▲. Bar marks period of water restriction in Pre- and Post-dry irrigation treatments. S.E. based on 22 D.F.

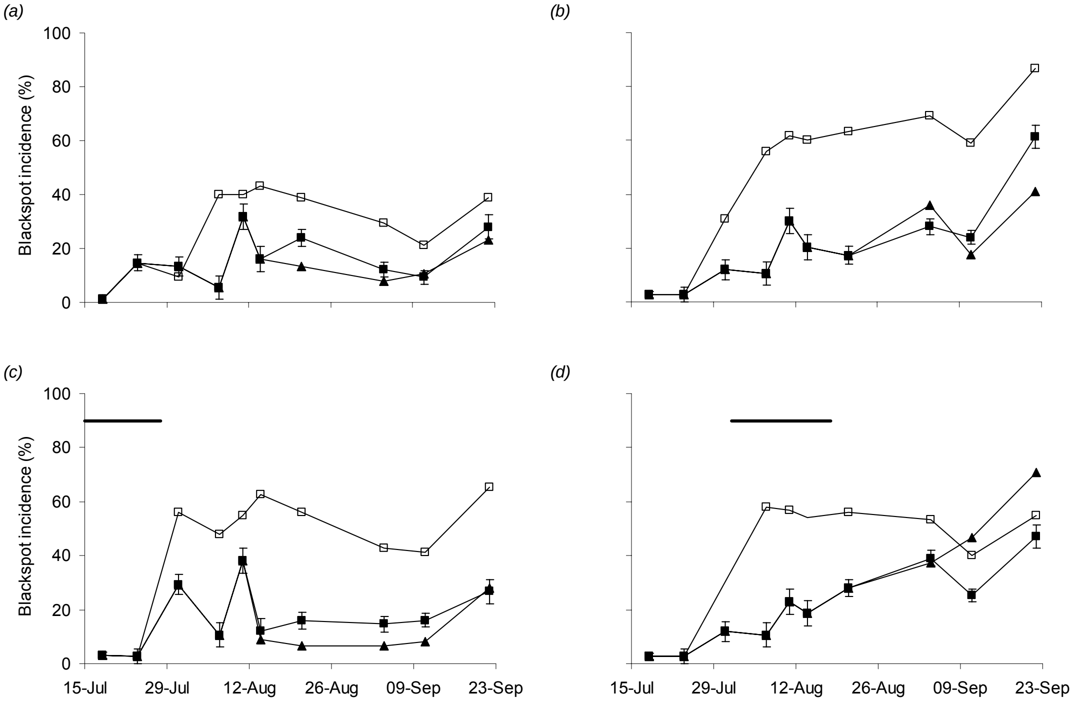


FIGURE 25. DEPTH OF INTERNAL DAMAGE IN EXPT 3

(a) Unirrigated; *(b)* Irrigated; *(c)* Pre-dry; *(d)* Post-dry. Undefoliated, ■; Defoliated Pre-dry, □; Defoliated Post-dry, ▲. Bar marks period of water restriction in Pre- and Post-dry irrigation treatments. S.E. based on 22 D.F.

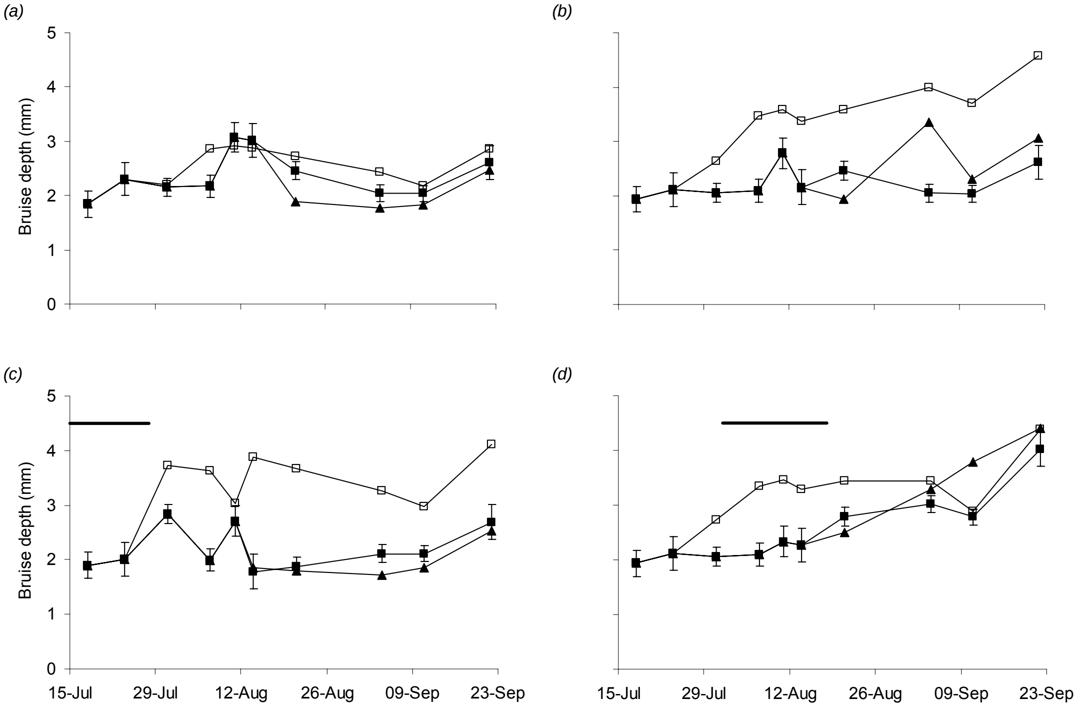


TABLE 9. INTERNAL DAMAGE INCIDENCE, BLACKSPOT INCIDENCE AND DEPTH OF DAMAGE ON 4 AND 11 SEPTEMBER IN EXPT 3

		Damage incidence (%)		Blackspot incidence (%)		Depth of damage (mm)	
Irrigation	Defoliation	4 Sep	11 Sep	4 Sep	11 Sep	4 Sep	11 Sep
Unirrigated	Undefoliated	23	23	12	9	2.04	2.61
Unirrigated	Pre-dry	39	27	29	21	2.17	2.86
Unirrigated	Post-dry	12	16	8	11	1.83	2.48
Irrigated	Undefoliated	35	39	28	24	2.61	3.14
Irrigated	Pre-dry	72	63	69	59	3.70	4.57
Irrigated	Post-dry	52	23	36	18	2.30	3.05
Pre-dry	Undefoliated	23	19	15	16	2.11	2.69
Pre-dry	Pre-dry	48	49	43	41	2.98	4.11
Pre-dry	Post-dry	9	16	7	8	1.86	2.53
Post-dry	Undefoliated	43	33	39	25	2.78	4.02
Post-dry	Pre-dry	67	43	53	40	2.88	4.38
Post-dry	Post-dry	45	60	37	47	3.78	4.41
	S.E. (22 D.F.)	6.45	5.76	5.73	4.97	0.148	0.315

Experiment 4

Throughout the season, bruising was generally lower for Unirrigated crops than for Irrigated and cultivation regime had no significant effect (Figure 26). There was some external cracking caused by the higher energy (1.0 J) of the falling bolt towards the end of the season compared with Expt 2. As tubers re-hydrated during August, cracking increased but only 3-4 % of tubers were affected at the latest harvests and cracking was unrelated to cultivation or irrigation treatments. Most of the internal damage was blackspot bruising in the last month of the season. At final harvest, Irrigated crops still had significantly greater bruising than Unirrigated (Table 10), with a mean blackspot incidence of *c.* 45 % *c.f.* 5 % in Expt 2 (0.5 J energy). Rate of nitrogen fertilizer had no effect on bruising at final harvest (Table 10).

FIGURE 26. BRUISING IN EXPT 4

(a) internal damage incidence; *(b)* blackspot incidence; *(c)* bruise depth. Cult Dry, Unirrigated, ■; Cult Dry, Irrigated, □; Cult Wet, Unirrigated, ▲; Cult Wet, Irrigated, △. Mean of 0 and 300 kg N/ha. S.E. based on 6 D.F.

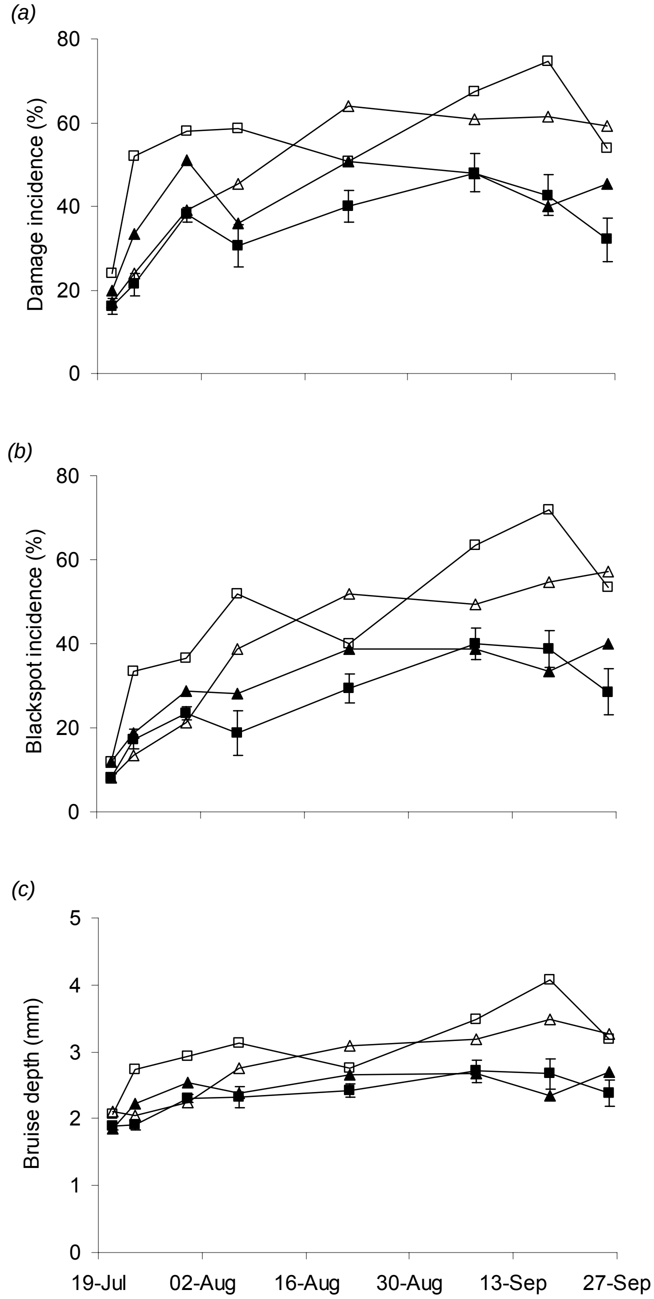


TABLE 10. INTERNAL DAMAGE INCIDENCE, BLACKSPOT INCIDENCE AND DEPTH OF INTERNAL DAMAGE ON 26 SEPTEMBER IN EXPT 4

Cultivation	Irrigation	N rate (kg/ha)	Damage incidence (%)	Blackspot incidence (%)	Depth of damage (mm)
Dry	Unirrigated	0	32	28	2.32
Dry	Unirrigated	300	32	29	2.44
Dry	Irrigated	0	57	56	3.32
Dry	Irrigated	300	51	51	3.05
Wet	Unirrigated	0	53	49	2.94
Wet	Unirrigated	300	37	31	2.46
Wet	Irrigated	0	56	52	2.94
Wet	Irrigated	300	63	63	3.61
	S.E. (6 D.F.)		11.9	12.0	0.403
	S.E. (same Cult x Irrig)		7.2	7.6	0.308

Experiment 5

Using the standard impact energy of 0.5 J, blackspot bruising appeared during the second week of July, 1-4 weeks earlier than any other season (Figure 27*b*). Crop emergence was 8-14 days earlier than in Expts 1 and 2 but the incidence of blackspot at the first harvest on 18 July was *c.* 25 %, a value not reached until mid-September in some years (e.g. Expt 1). Given the inexorable increase in blackspot during the season, it is not surprising that blackspot incidence at final harvest in Expt 5 was the highest recorded in the four years of experiments. In conjunction with the earlier blackspot bruising observed in 2007, whitespot bruising was also very high when impacting started in mid-July (Figure 27*a*). The mean depth of internal damage was 6.6 mm by the end of the season (Figure 27*c*), again considerably higher than in any previous year. In summary, blackspot bruising started earlier, was more prevalent and damage was deeper in Expt 5 than in Expts 1-3.

Over the course of the season, there were significant differences between irrigation regimes and between crops which were defoliated or left to senesce naturally but by the beginning of September, most of these differences had been eroded (Table 11). There was no significant difference in internal damage or blackspot between Unirrigated and Irrigated treatments when impact testing commenced on 18 July but the differential in SMD was only 16 mm between the two regimes from the beginning of June through to mid-July. Maintaining the crops fully-irrigated during late July and early August increased bruising incidence (Figure 27*a,b*) and the width of bruises but only temporarily compared with Unirrigated or Pre-dry crops. Once senescence started, irrigation regime had no effect on bruising as all crops except Post-dry returned to close to field capacity during August owing to persistent rain in the latter half of August. Post-dry crops were covered during this time but the canopy senesced so rapidly and the evaporative demand was so low that only a moderate SMD was developed and this did not affect bruising compared with other irrigation regimes.

FIGURE 27. TIMECOURSE OF *(A)* INTERNAL DAMAGE INCIDENCE, *(B)* BLACKSPOT INCIDENCE AND *(C)* BRUISE DEPTH IN EXPT 5

Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 6-21 D.F.

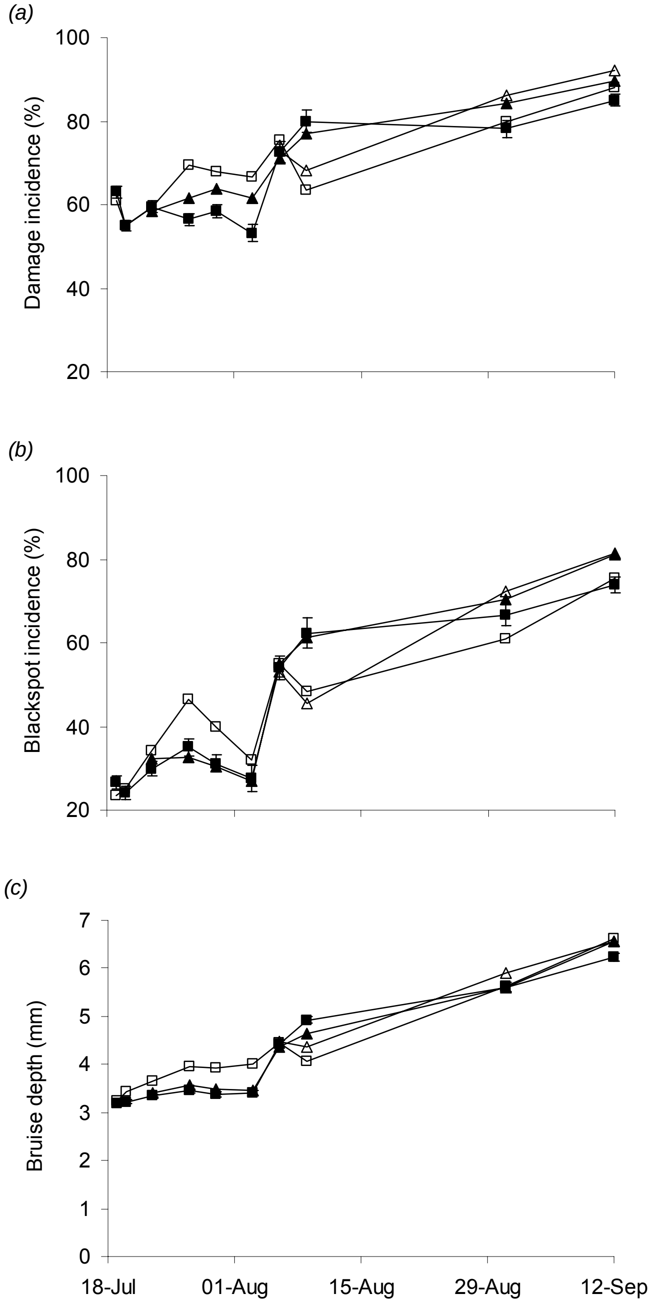


TABLE 11. INTERNAL DAMAGE INCIDENCE, BLACKSPOT INCIDENCE AND BLACKSPOT VOLUME ON 9 AUGUST AND 12 SEPTEMBER IN EXPT 5

		Damage incidence (%)		Blackspot incidence (%)		Blackspot volume (mm^3)	
Irrigation	Defoliation	9 Aug	12 Sep	9 Aug	12 Sep	9 Aug	12 Sep
Unirrigated	Undefoliated	80	85	62	74	46	116
Unirrigated	Defoliated	78	91	60	77	63	148
Irrigated	Undefoliated	64	88	48	75	43	139
Irrigated	Defoliated	78	91	51	81	57	145
Pre-dry	Undefoliated	77	89	61	81	50	127
Pre-dry	Defoliated	78	88	62	78	62	143
Post-dry	Undefoliated	68	92	46	81	41	139
Post-dry	Defoliated	77	84	67	79	68	157
	S.E. (21 D.F.)	5.5	2.7	7.3	3.6	6.0	6.1

Defoliation was carried out on half of the plots at the same time as in previous years (3 August) but the canopy had begun rapid senescence (ground cover *c.* 77 %) by this stage. It was the intention to test the effect of defoliation on a senescing crop in Expt 5 rather than on a crop with full canopy cover (Expts 1 and 3), however natural senescence was very rapid in 2007 and non-defoliated crops were almost completely dead within 4 weeks from the onset of senescence (24 July). Albeit not as extreme as in Expts 1 and 3, defoliation was carried out on a hot day (25 °C) in the middle of a 5-day period of hot weather (mean 25 °C, maximum 30 °C). Three days after defoliation, flailed crops had deeper and wider blackspot bruises and internal damage than Undefoliated crops. Although the incidence of bruising was not significantly different at every harvest during the period from defoliation to final harvest, the differences in bruise volume, although small, remained significantly greater in Defoliated crops than Undefoliated throughout the entire harvesting period (Table 11). The negative effects of defoliation on bruising were smaller than in Expts 1 and 3 and apparently unrelated to the irrigation regime the crops had received prior to defoliation. This observations adds credence to the theory that defoliation itself has an effect on bruising but the magnitude of its effects depend on stage of canopy senescence and the moisture regime around the time of defoliation.

Experiment 6

Blackspot bruising was much higher in Expt 6 (final harvest 60 % incidence) than in Expt 4 (45 % incidence) despite halving the impact energy from 1.0 to 0.5 J between the two experiments. From the time sampling commenced (16 August), blackspot bruising was generally less prevalent and bruises mostly shallower in Irrigated crops than in Unirrigated (Figure 28). This was the opposite effect to Expt 4, although by final harvest when the plots were all well-senesced (35-55 % ground cover), differences in bruising between irrigation treatments in Expt 6 were no longer apparent (Table 12). Cultivation regime had no significant effect on bruising (Figure 28, Table 12). At final harvest, blackspot bruising incidence decreased as nitrogen level increased from 0 kg N/ha to 300 kg but the bruises became deeper as nitrogen level increased (Table 12). This effect could be a function of the increased tuber size of crops supplied with more nitrogen in Expt 6 as the peri-medullary layer (the zone where blackspot bruising occurs) would be deeper in larger tubers. Additionally, mean cell size in the peri-medullary layer has been found to decrease as N fertilizer level increases (Reeve *et al.* 1971), which tends to increase tissue strength.

FIGURE 28. BLACKSPOT INCIDENCE IN EXPT 6

Cultivated Dry, Unirrigated, ■; Cultivated Dry, Irrigated, □; Cultivated Wet, Unirrigated, ▲; Cultivated Wet, Irrigated, △. 150 kgN/ha treatment only. S.E. based on 9 D.F.

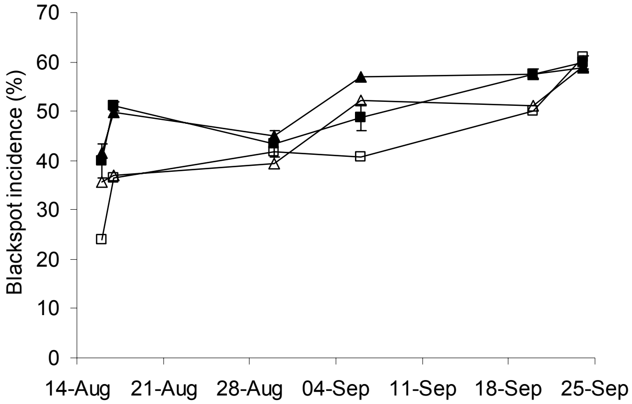


TABLE 12. INTERNAL DAMAGE INCIDENCE, BLACKSPOT INCIDENCE AND BLACKSPOT DEPTH ON 24 SEPTEMBER IN EXPT 6

Cultivation	Irrigation	Nitrogen rate (kg/ha)	Internal damage incidence (%)	Blackspot incidence (%)	Blackspot depth (mm)
Cult Dry	Unirrigated	0	77	69	4.02
		150	68	60	4.54
		300	68	51	4.83
	Irrigated	0	75	66	4.25
		150	73	59	4.71
		300	68	58	4.62
Cult Wet	Unirrigated	0	79	70	4.37
		150	66	56	4.82
		300	65	51	4.79
	Irrigated	0	79	65	4.28
		150	73	61	4.52
		300	69	52	4.98
		Mean for Cult Wet	72	59	4.63
		Mean for Cult Dry	71	60	4.50
		Mean for Unirrigated	70	59	4.56
		Mean for Irrigated	72	60	4.56
	S.E. for Cult or Irrig. mean (9 D.F.)		2.3	2.7	0.063
	S.E. for Cult or Irrig. (24 D.F.)		4.5	5.4	0.180
	S.E. for Cult and Irrig. (24 D.F.)		3.9	4.6	0.192

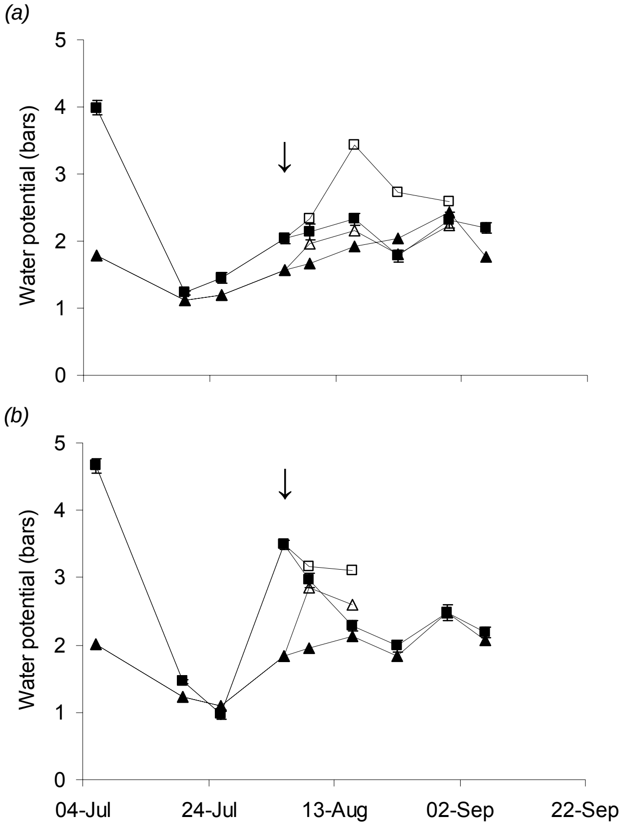
Tuber Water Potential WP

Experiment 1

At the initial harvest on 6 July, WP was increased considerably by withholding irrigation but there was no difference between Unirrigated and Irrigated following 53 mm of rain in the second week of July. Dry, highly evaporative weather in the second half of July caused WP to increase faster in Unirrigated crops than in Irrigated but the effect was greater in Smith's Comet than Lady Rosetta (Figure 29). By the end of August any effects of irrigation on WP had disappeared. Initially, Smith's Comet had a higher WP than Lady Rosetta but just prior to defoliation they were similar and did not differ thereafter. Surprisingly, WP generally increased in defoliated crops soon after defoliation compared with crops left to senesce naturally (Figure 29). Two weeks after defoliation, WP was still greater in Unirrigated, Defoliated crops than in Unirrigated Undefoliated crops but in Irrigated crops, defoliation regime had no effect on WP by this time. The effects of defoliation in Unirrigated crops on WP extended until the end of August, after which there were no significant differences in WP. Cutting roots had no effect on WP in Irrigated crops. Cutting was only significant in Unirrigated treatments which were defoliated (data not shown). In Lady Rosetta, root cutting reduced WP whereas in Smith's Comet it increased it. The effect of cutting roots on WP disappeared three weeks after the treatment was carried out.

FIGURE 29. TUBER WATER POTENTIAL IN EXPT 1

(a) Lady Rosetta; *(b)* Smith's Comet. Unirrigated, Undefoliated, ■; Unirrigated, Defoliated, □; Irrigated, Undefoliated, ▲; Irrigated, Defoliated, △. Defoliation treatments applied on 6 August (↓). S.E. based on 12-28 D.F.



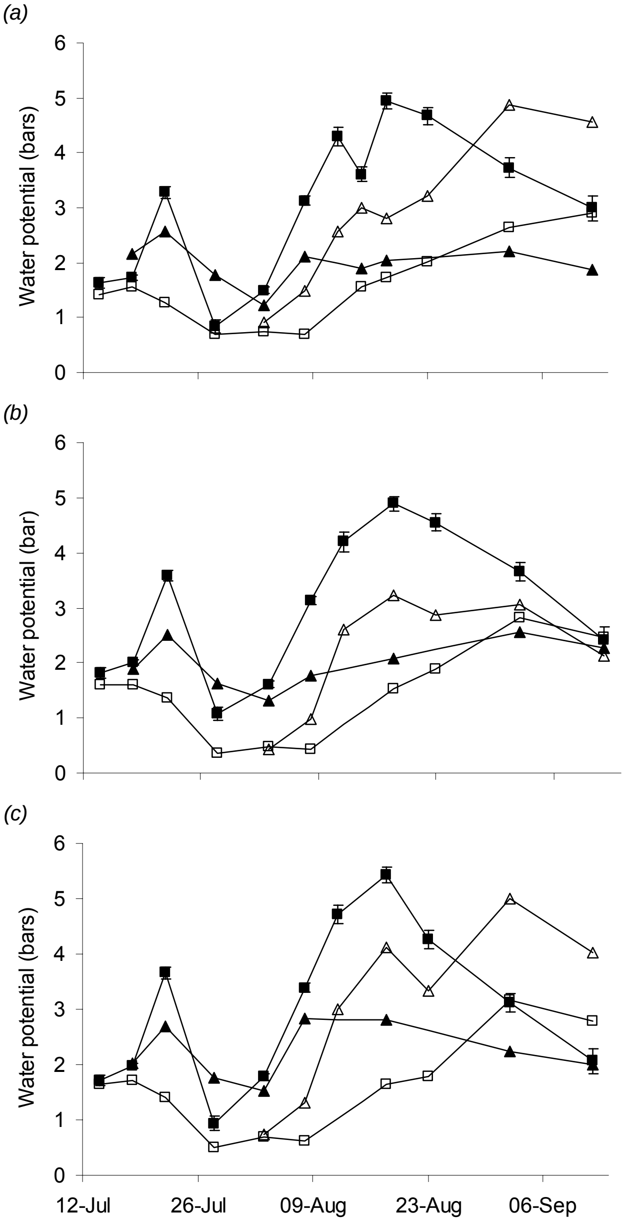
Experiment 2

Tubers were slightly less than fully hydrated in both Unirrigated and Irrigated crops when measurement of WP started on 14 July (Figure 30). As irrigation continued, WP dropped and was maintained at very low levels (*c*. 0.5 bars) in all three varieties until mid-August. Following this, despite maintaining SMDs below 20 mm in Irrigated crops, tuber WP increased and stabilized at *c*. 2.5-2.9 bars in mid-September, again with no difference between the varieties. Unirrigated plots attained the highest tuber WPs (4.9-5.4 bars) in mid-August but these decreased thereafter until they were the same as Irrigated treatments by mid-September.

During the Pre-dry drought-stress period (15 July to 4 August), tuber WP initially increased slightly but then decreased over the next two weeks (Figure 30). It was sunny and hot and the evaporative demand was high (ET0 4.3 mm/day) in the first week of the drought stress period but ET0 was much lower (1.9 mm/day) in the following week owing to low light levels. The tubers rehydrated under this low evaporative demand despite the SMD increasing from 50 mm to 60 mm over this period. In the last week of the Pre-dry stress period, evaporative demand increased again (ET_0 3.2 mm/day) and tuber WP increased.

By contrast, tuber WP in the Post-dry treatments increased rapidly on ceasing irrigation and continued to increase throughout the stress period despite the overall ET_0 being only 2.9 mm/day, although there was no extremely low ET_0 in this period (Figure 30). In Lady Rosetta and Smith's Comet, WP continued to increase until the end of August despite irrigation being applied frequently after the end of the drought period (Figure 30). Ground covers senesced rapidly in the last week of the Post-dry period. In Maris Piper, however, WP did not increase once the drought period had ended and irrigation had re-commenced. At the end of the measurement period (12 September), tuber WP was still greater in the Post-dry water treatment in Lady Rosetta and Smith's Comet than Unirrigated or Pre-dry. Therefore, withholding water during the period after the onset of crop senescence combined with an average evaporative demand (ET_0 2.9 mm/day) had a much greater effect on tuber WP than a water stress period applied pre-senescence and in Lady Rosetta and Smith's Comet the effect was maintained until the end of the season. In consequence the Post dry and Unirrigated treatments might be expected to have a higher incidence of blackspot bruising than fully irrigated crops in this experiment but as shown earlier, this was not the case.

FIGURE 30. TUBER WATER POTENTIAL IN EXPT 2
(a) Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet. Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 8-16 D.F.

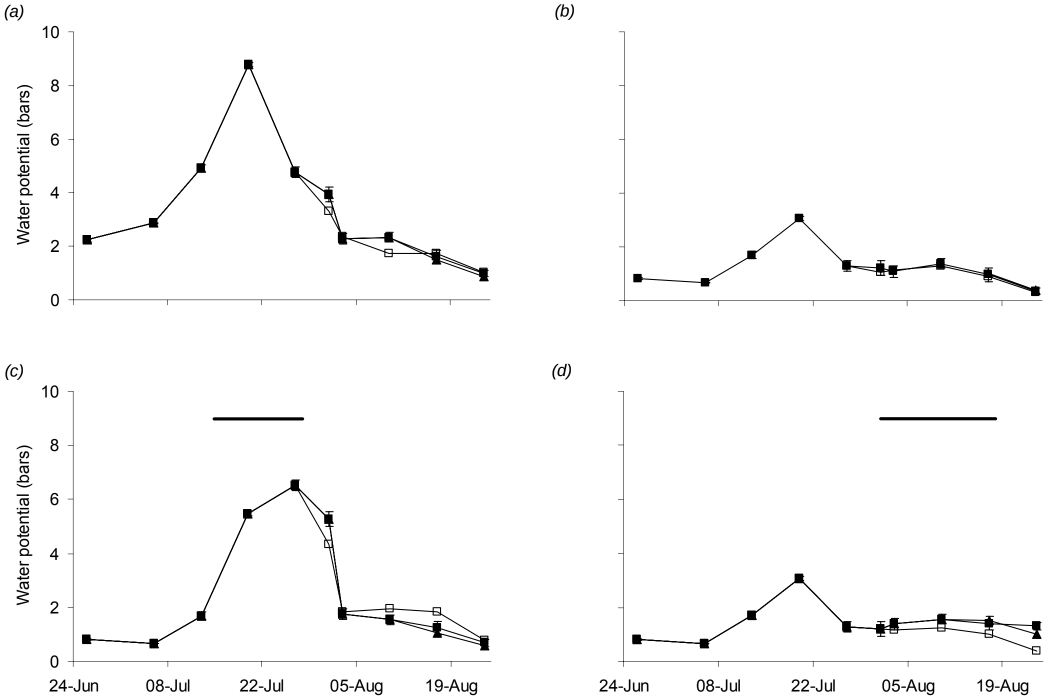


Experiment 3

Tubers became severely dehydrated during mid-July where irrigation was withheld, with WP reaching 8.8 bars in Unirrigated crops and 6.5 bars where the water stress was more temporary (Pre-dry), almost double the maximum WP recorded in Expts 1 and 2. It proved impossible during this period of hot weather in 2006 to prevent WP rising to over 3 bars in fully-irrigated plots despite being able to irrigate with 24 mm every 4 days and maintain the SMD < 27 mm (Figure 31). After this hot period, the wetter, cooler August that followed caused WP in all treatments to decrease to very low values by the end of August. Therefore, for almost the entire commercial harvesting period for this typical Lady Rosetta crop, tubers would have been deemed fully hydrated and at a low risk of suffering blackspot bruising according to the original hypothesis of Smittle *et al.* (1974). However, in Expt 3 tubers reached their final WP having taken a very different route compared with Expts 1 and 2.

Tubers in plots which were defoliated at the end of the Pre-dry period initially became hydrated more rapidly than those which were left Undefoliated but the differences were small and not always significant (Figure 31). Tubers from crops which were defoliated at the end of the Post-dry period were sufficiently hydrated for there to be no further decrease in WP following haulm removal.

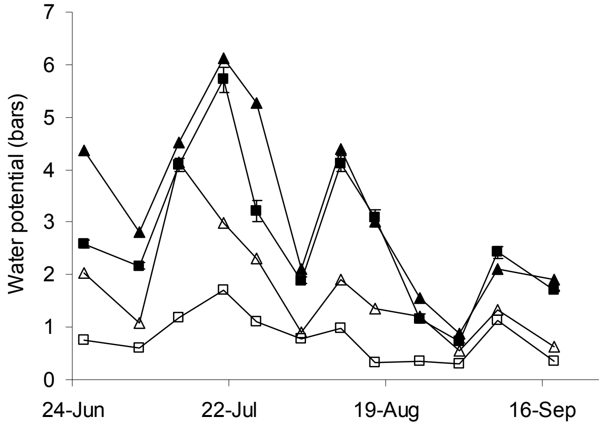
FIGURE 31. TUBER WATER POTENTIAL IN EXPT 3
(a) Unirrigated; *(b)* Irrigated; *(c)* Pre-dry; *(d)* Post-dry. Undefoliated, ■; Defoliated Pre-dry, □; Defoliated Post-dry, ▲. Bar marks period of water restriction in Pre- and Post-dry irrigation treatments. S.E. based on 6-16 D.F.



Experiment 4

Tuber WP showed the same seasonal pattern in Maris Piper as in Lady Rosetta, increasing to a peak of *c.* 6 bars (Unirrigated) in mid-late July and then gradually decreasing throughout August (Figure 32). Unirrigated crops had significantly greater tuber WP than Irrigated throughout the entire season, even into mid-September. With scheduled irrigation, it was possible to maintain tubers grown in soil free from obvious compaction at a WP of < 1.7 bars throughout the season. Particularly during the early part of the season, crops grown in compacted soil had higher tuber WP than those in uncompacted soil and therefore should have bruised more easily according to the hypothesis of Smittle *et al.* (1974).

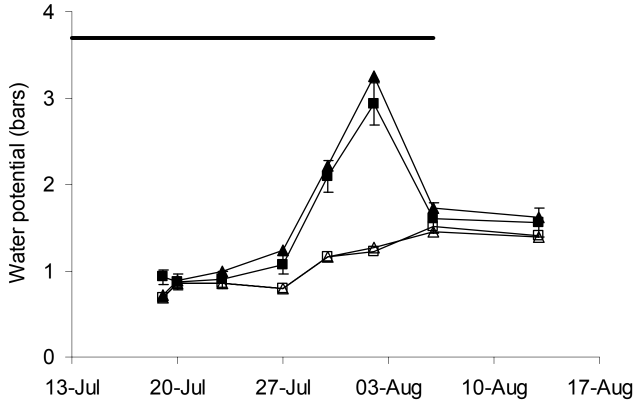
FIGURE 32. TUBER WATER POTENTIAL IN EXPT 4
Cult Dry, Unirrigated, ■; Cult Dry, Irrigated, □; Cult Wet, Unirrigated, ▲; Cult Wet, Irrigated, △ 300 kg N/ha treatments only. S.E. based on 6 D.F.



Experiment 5

Measurement of tuber WP began when impact testing began and soon after the start of the Pre-dry stress period. A period of measurement every 1-4 days followed, with the measurements being taken between 08:00 and 10:00 h each morning (Figure 33). There were no significant differences in tuber WP on 19 July and over the next 8 days there was little increase in WP of the Unirrigated and Pre-dry treatments. Evaporative demand was low over this period. Once the SMD in these latter two treatments exceeded the Limiting SMD, tuber WP increased rapidly and slightly faster in Pre-dry than Unirrigated (although not significantly). Tubers from these two stress treatments rewetted between 2 and 6 August but not as a consequence of receiving rainfall or irrigation. Evaporative demand was high (ET_0 4.4-5.2 mm) between these two dates and tubers might have been expected to dehydrate. However, crop senescence on 6 August was advanced (19 and 34 % GC in Unirrigated and Pre-dry, respectively on 7 August) and the sparse leaf canopy would have little requirement for water supply from tubers. When measurement stopped on 13 August owing to senescent stolons, all irrigation treatments had reached the same tuber WP and, from previous observations, would have been expected to remain in a similar water status throughout the subsequent harvesting period

FIGURE 33. TUBER WATER POTENTIAL IN EXPT 5
Unirrigated, ■; Irrigated, □; Pre-dry, ▲; *(d)* Post-dry, △. Undefoliated treatment only. Bar marks period of water restriction in Pre-dry irrigation treatment. S.E. based on 9 D.F.



Relationship between leaf and tuber water potential

Experiment 3

A detailed study of the relationship between leaf and tuber WP in Unirrigated and Irrigated crops was conducted on two occasions during the season. The first was on a very hot day during the middle of a sustained period of hot and dry weather (18 July) and the second two weeks later on a dull, cool day (3 August). The SMD at 08:00 h and the Limiting SMD for the measurement day are shown in Table 13 along with the Reference Crop ET_0 and the modelled ET for the crop. The SMD was very high in the Unirrigated crop on 18 July and substantially greater than the Limiting SMD and this would have restricted water use whereas the Irrigated crop was irrigated the previous afternoon and had a deficit well below the Limiting SMD and would have used water at a rate close to the potential of the atmosphere. By contrast, on 3 August, the evaporative demand was only half the expected average and both crops should have been able to extract sufficient water to match the potential rate.

TABLE 13. EVAPORATIVE DEMAND AND SOIL MOISTURE MOISTURE DEFICITS IN EXPT 3 FOR TWO CONTRASTING DAYS WHEN LEAF AND TUBER WATER POTENTIALS WERE MEASURED

Date	Variable (mm)	Unirrigated	Irrigated
18 July	ET_0	5.53	5.53
	SMD	67	8
	Limiting SMD	22	22
	ET_{crop}	1.42	5.50
3 August	ET_0	1.55	1.55
	SMD	55	0
	Limiting SMD	57	57
	ET_{crop}	1.37	1.66

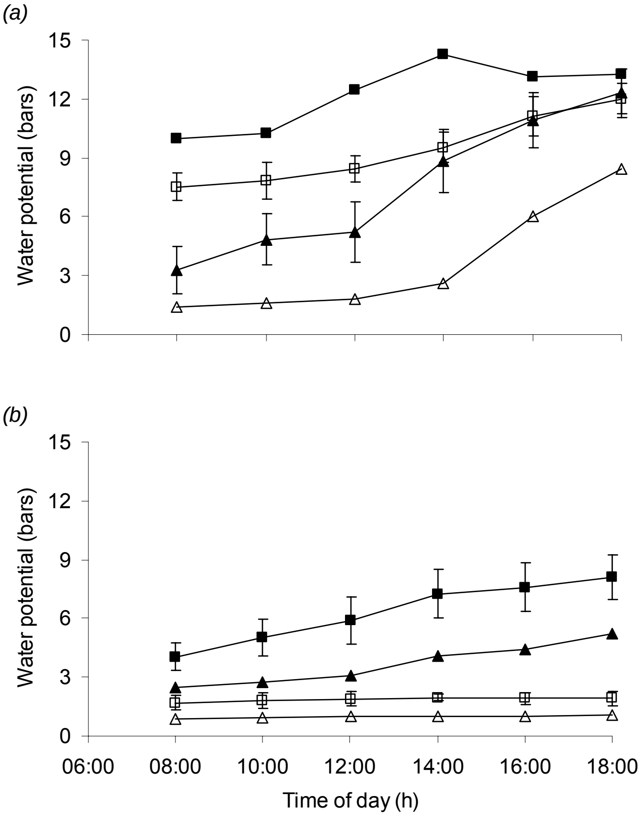
In addition to the two intensive studies, leaf WP was measured approximately every 10 days between 09:00 and 10:00 h starting on 15 June. Irrigated crops had consistent leaf WP of *c*. 2.6-3.0 bar up until the hot weather in July whilst the Unirrigated crops had regular readings of *c*. 7.3-7.7 bar.

On 18 July, without irrigation leaves were dehydrated initially in the morning and lost turgor until 14:00 h when there was little further change (Figure 34*a*). Tubers dehydrated slowly throughout the day reaching 12 bar by 18:00 h and therefore close to the leaf WP. Leaves in Irrigated plots started hydrated and lost turgor slowly until mid-day when the WP started increasing rapidly. By the end of the measurement period at 18:00 h, their WP was similar to the Unirrigated leaves. Tuber WP in Irrigated crops barely changed until 14:00 h when it began to increase rapidly.

On 3 August, leaves started off more hydrated than on 18 July and WP increased slowly during the day (Figure 34*b*). Tubers, in contrast to the earlier sampling date, remained at a constant WP throughout the day and Irrigated tubers had a lower WP at 18:00 h than their overnight values on 17-18 July.

Tubers for bruise assessment were always taken between 08:00 and 10:00 h along with the weekly tuber WP measurements. On 18 July, tubers from Irrigated plots would have been in a very different hydration status if harvested mid-afternoon since their WP would have increased by a factor of four from mid-morning measurements. On 3 August, the WP measurements would indicate that bruising susceptibility should not have altered throughout the day and therefore highlight the potential variation in apparent bruising sensitivity if tubers are harvested at different times of the day. These findings are reported in the section relating bruising to tuber WP (p. **Error! Bookmark not defined.**).

FIGURE 34. LEAF AND TUBER WATER POTENTIALS ON TWO CONTRASTING OCCASIONS IN EXPT 3
(a) 18 July; *(b)* 3 August. Leaf, Unirrigated, ■; Tuber, Unirrigated, □; Leaf, Irrigated, ▲; Tuber, Irrigated, △. S.E. based on 5 D.F. (6 replicates).

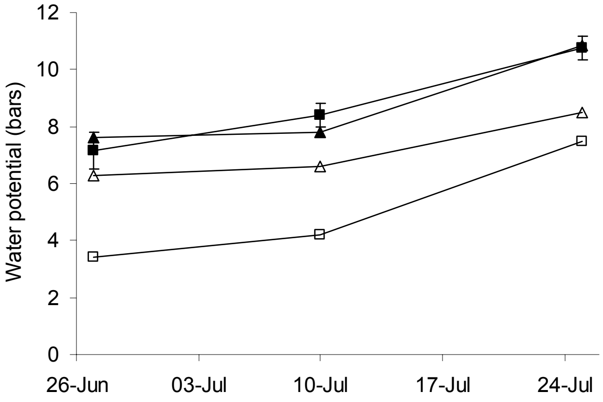


Experiment 4

A small number of measurements were made of leaf WP in Expt 4. These showed that soil compaction caused leaves to be less turgid than those from plants grown in loose soil. These effects were only observed in Irrigated plots where the leaves had lower WPs than in Unirrigated (Figure 35).

FIGURE 35. LEAF WATER POTENTIALS (WP) ON THREE OCCASIONS IN EXPT 4

Cult Dry, Unirrigated, ■; Cult Dry, Irrigated, □; Cult Wet, Unirrigated, ▲; Cult Wet, Irrigated, △. 300 kg N/ha treatments only. S.E. based on 9 D.F.

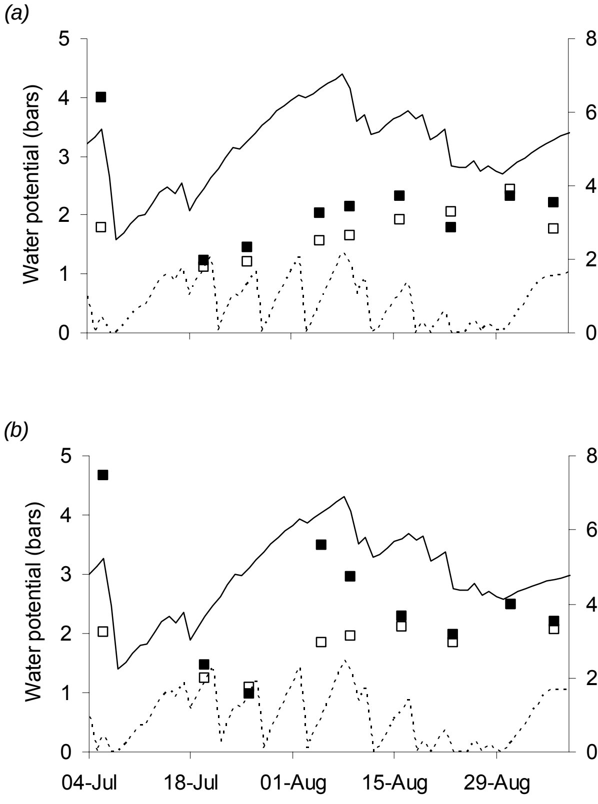


Relationship between tuber water potential and soil moisture deficit

Experiment 1

Soil moisture deficit was not a good predictor of tuber WP in Expt 1 (Figure 36). As the difference in SMD between Unirrigated and Irrigated treatments increased during mid-July to mid-August there was a much smaller differential in tuber WP. By the end of August there was no difference in WP between irrigation treatments or varieties despite there being a 30-37 mm difference in SMD although there was 38 mm of rain in the last 10 days of August. The final measurement of tuber WP was *c.* 2.1 bars for all treatments.

Figure 36. Tuber water potential and soil moisture deficit (SMD) in Expt 1
(a) Lady Rosetta; *(b)* Smith's Comet. SMD: Unirrigated, solid line; Irrigated, dashed line. Water potential: Unirrigated, ■; Irrigated, □.



Experiment 2

Changes in tuber WP were generally related to changes in SMD up to the point where visible senescence occurred (i.e. loss of ground cover). Beyond this point, tuber WP responded less rapidly to small changes in SMD and there was a gradual decrease in WP as soils wetted up in the Unirrigated, Pre- and Post-dry irrigation treatments (Figures 37-39). However, tuber WP in Irrigated crops increased over the same period. The heavy rain in September returned all treatments to close to field capacity (*c.* 3 mm SMD) and the WP in all Maris Piper plots ended at very similar values (2.1-2.4 bars). In contrast, Post-dry Lady Rosetta and Smith's Comet still had high tuber WP (4.0-4.6 bars) at the end of the season despite the low SMD. Other treatments were more similar (2.0-2.9 bars) in these two varieties (i.e. similar to Expt 1). Clearly, the late water stress imposed on Post-dry crops in early August altered their ability to re-hydrate tubers during September. The Post-dry plots lost GC most rapidly after being water stressed and so possibly the root system was dead and incapable of absorbing the freely-available water in the soil. The importance of the response in tuber WP during senescence is crucial in validating the hypothesis that irrigation at desiccation re-hydrates tuber sufficiently so that they do not bruise at harvest. Clearly, the timing of the irrigation (and the quantity applied) during senescence is important in some varieties. The changes in tuber WP in relation to bruising is discussed later.

FIGURE 37. TUBER WATER POTENTIAL AND SOIL MOISTURE DEFICIT (SMD) IN LADY ROSETTA IN EXPT 2
(a) Unirrigated; (b) Irrigated; (c) Pre-dry; (d) Post-dry. Water potential ■; soil moisture deficit, —.

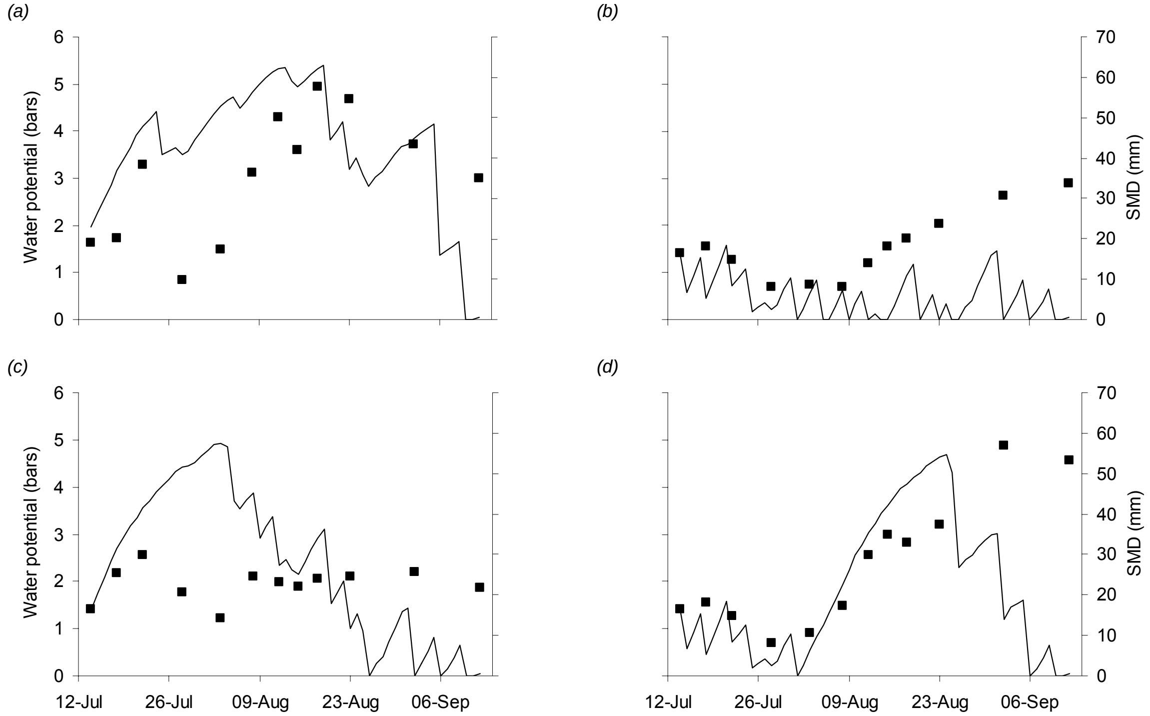


FIGURE 38. TUBER WATER POTENTIAL AND SOIL MOISTURE DEFICIT (SMD) IN MARIS PIPER IN EXPT 2
(a) Unirrigated; (b) Irrigated; (c) Pre-dry; (d) Post-dry. Water potential ■; soil moisture deficit, —.

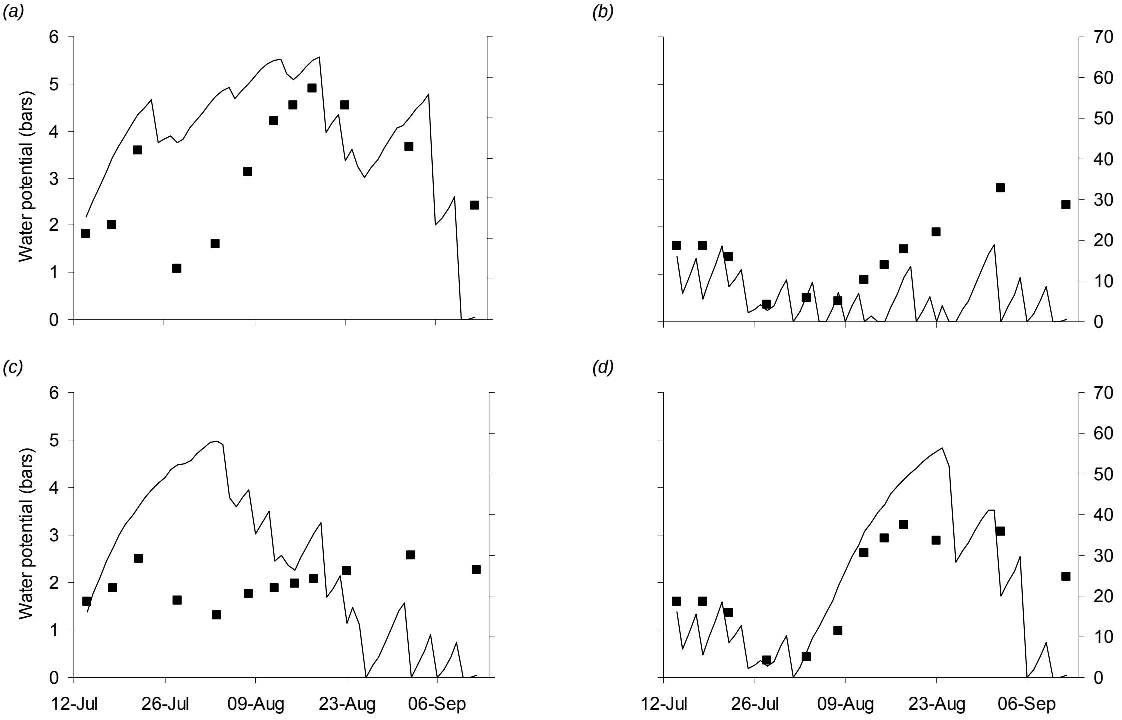
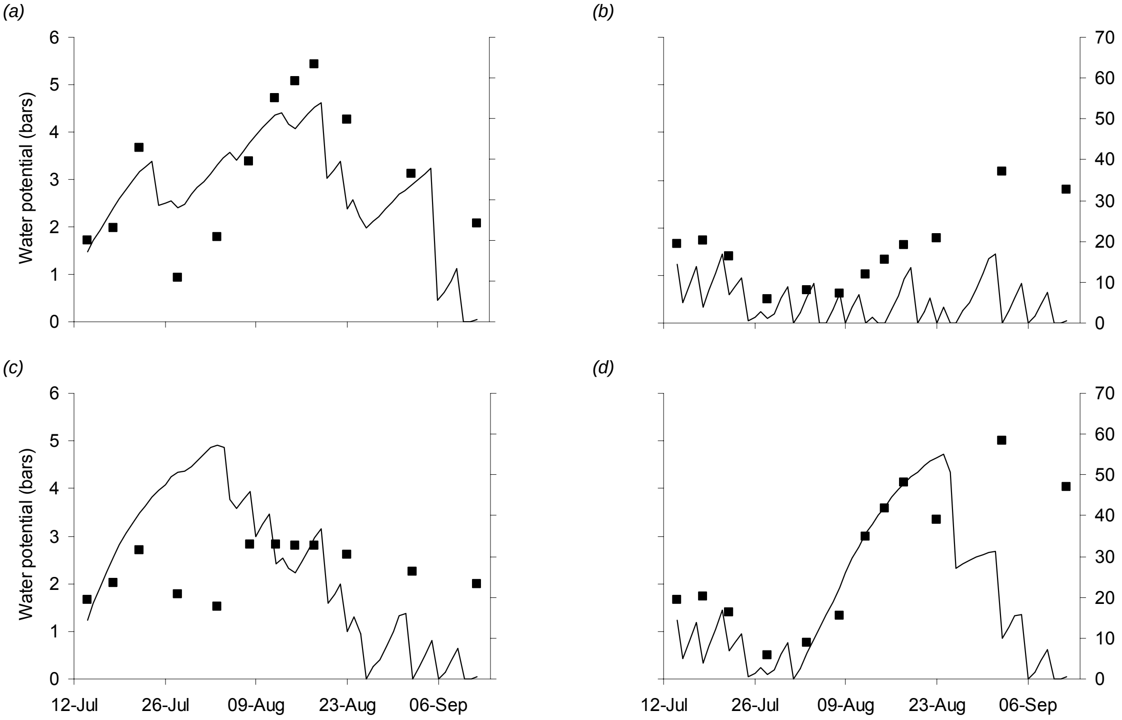


FIGURE 39. TUBER WATER POTENTIAL AND SOIL MOISTURE DEFICIT (SMD) IN SMITH'S COMET IN EXPT 2
(a) Unirrigated; (b) Irrigated; (c) Pre-dry; (d) Post-dry. Water potential ■; soil moisture deficit, —.



Experiment 3

Tuber WP in undefoliated crops closely tracked changes in SMD in a directional manner particularly in the Pre-dry irrigation treatment (Figure 40). There was not a particularly close overall relationship between tuber WP and SMD (Figure 41) and this might be expected since (a) tuber WP necessarily lags changes in SMD (which can be almost instantaneous by comparison following an irrigation event) and (b) the rate of de- or re-hydration at a given SMD will depend on the evaporative demand, being slower to re-hydrate on hot days following an influx of water to the soil. This area merits further study.

Figure 40. Tuber water potential (■) and soil moisture deficit (SMD, —) in Expt 3
(a) Unirrigated; *(b)* Irrigated; *(c)* Pre-dry. Undefoliated crops only. Data not shown for Post-dry.

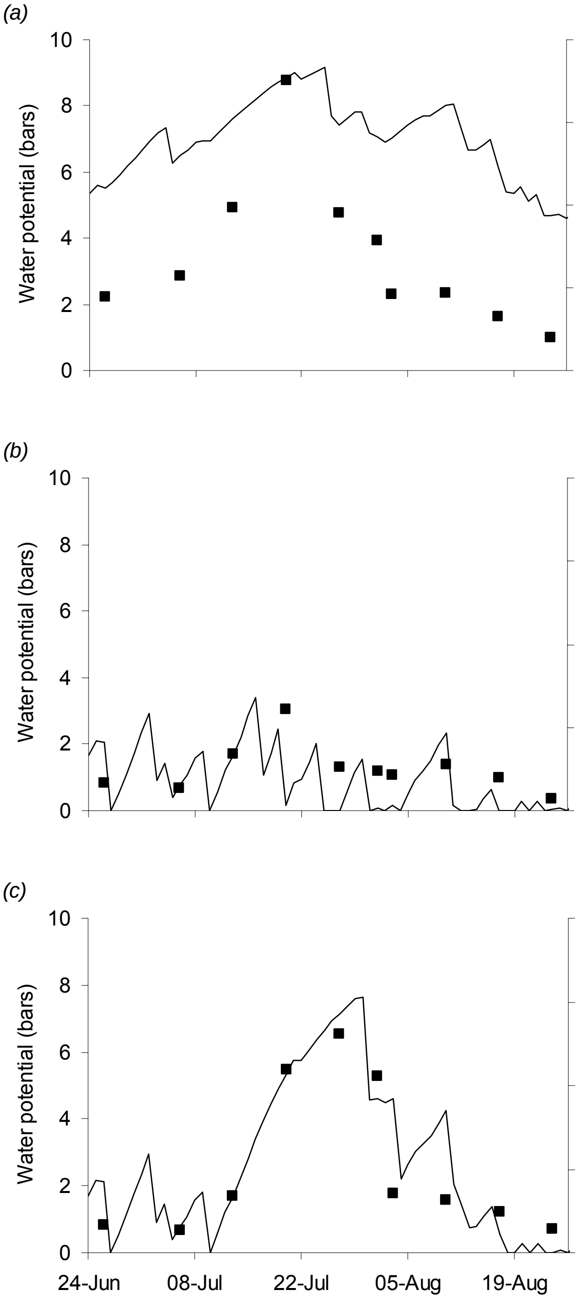
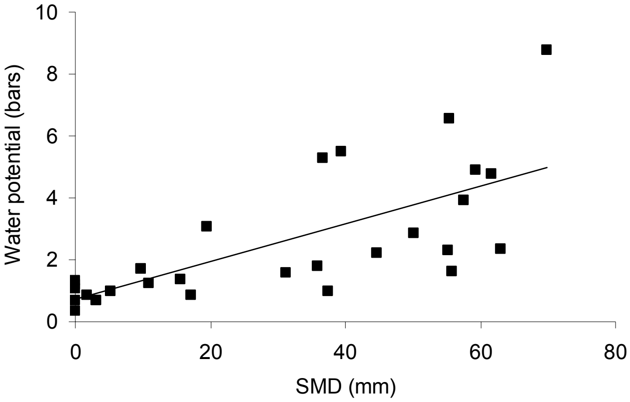


FIGURE 41. RELATIONSHIP BETWEEN TUBER WATER POTENTIAL (WP) AND SOIL MOISTURE DEFICIT (SMD) IN EXPT 3

Undefoliated crops only. Relationship: y=0.061x (±0.0067) +0.71, $R^2 = 0.67$.



Experiment 4

As in Expt 3, the directional changes in SMD were generally matched by changes in tuber WP (Figure 42). Tuber WP could be predicted quite closely from modelled SMD in the Cult Dry treatments but the Cult Wet plots had a larger range of tuber WPs for a given SMD (Figure). The CUF Scheduling model currently has only a simple means of accounting for the reduced water uptake observed in compacted soil as it adjusts the Limiting SMD *pro rata* according to modelled changes in rooting depth and root length density in specific horizons (Stalham *et al*. 2007) and this possibly contributed to the inaccuracy in estimating SMD.

FIGURE 42. TUBER WATER POTENTIAL (WP, ■) AND SOIL MOISTURE DEFICIT (SMD, —) IN EXPT 4

(a) Cult Dry Unirrigated; *(b)* Cult Dry Irrigated; *(c)* Cult Wet Unirrigated; *(d)* Cult Wet Irrigated.

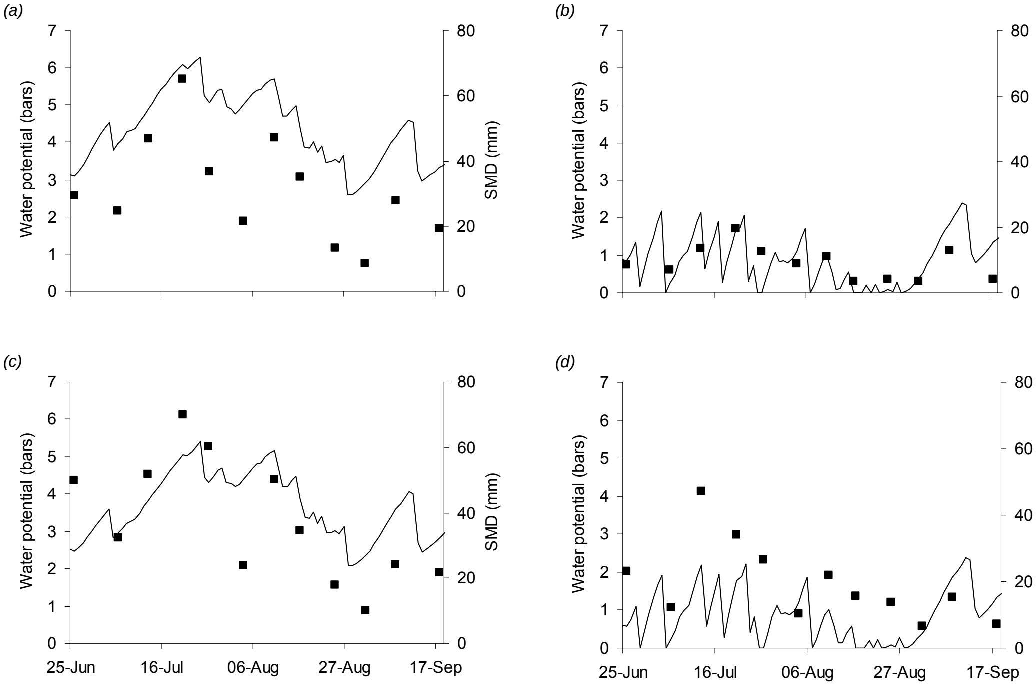
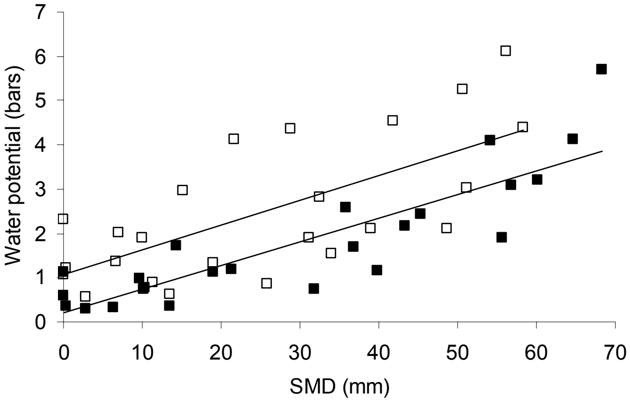


FIGURE 43. RELATIONSHIP BETWEEN TUBER WATER POTENTIAL AND SOIL MOISTURE DEFICIT (SMD) IN EXPT 4
Cult Dry ■, y=0.054x (±0.0037) +0.20, $R^2 = 0.85$; Cult Wet □, y=0.056x (±0.0065) +1.06, $R^2 = 0.57$. 300 kg N/ha treatments only.



Experiment 5

The relationship between tuber water potential and SMD is shown in Figure 44. There were only small differences in WP between Unirrigated and Irrigated crops when sampling commenced in mid-July but the actual SMDs were below the Limiting SMD and the little alteration in plant water balance might be expected. When larger differences in SMD were created between stressed treatments (Unirrigated and Pre-dry) and Irrigated, there were larger differences in tuber WP. Once rapid canopy senescence commenced, tubers quickly reached a low equilibrium WP (1.4-1.6 bars) there was little correlation between tuber WP and SMD. Therefore, there was only a moderate correlation between tuber WP and SMD when examining the data over the entire sampling period (Figure 45).

Figure 44. Tuber water potential (■) and soil moisture deficit (SMD, —) in Expt 5
(a) Unirrigated; *(b)* Irrigated; *(c)* Pre-dry; *(d)* Post-dry. Undefoliated crops only.

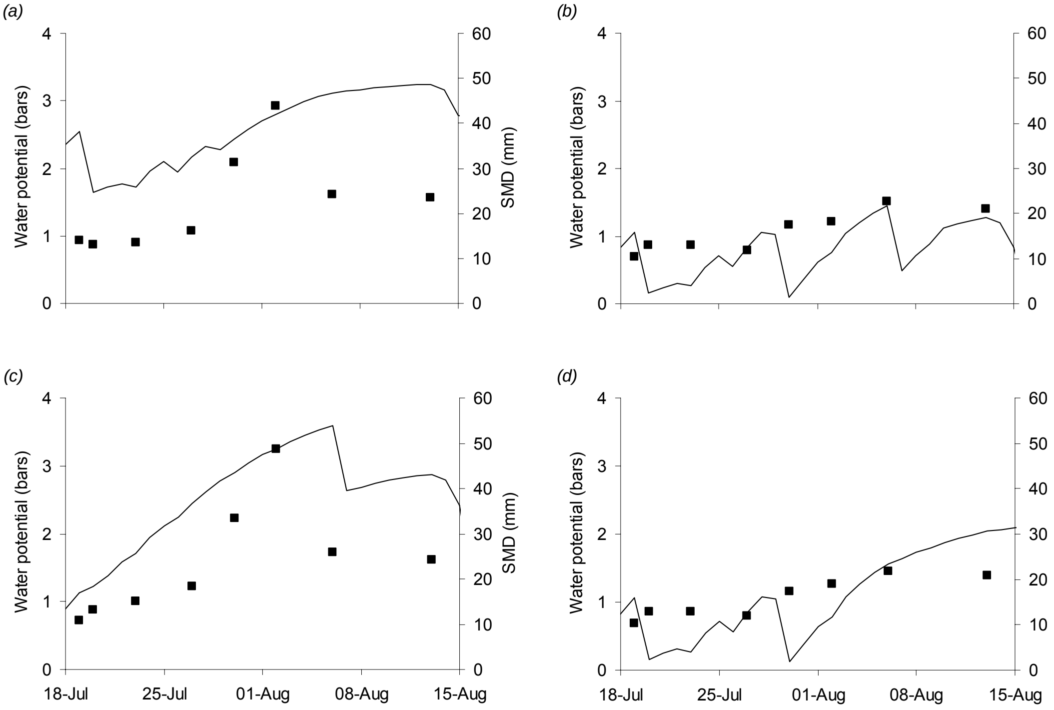
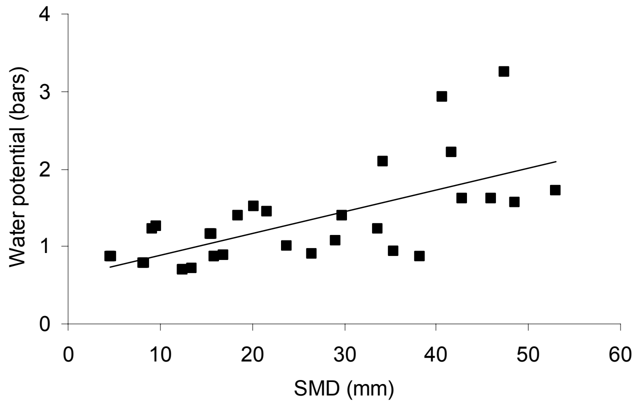


Figure 45. Relationship between tuber water potential and soil moisture deficit (SMD) in Expt 5
Relationship: y=0.028x (±0.0036) +0.60, $R^2 = 0.49$.



Relationship between bruising and tuber water potential

Experiment 1

An example of the variation in the relationship between bruising, WP and [DM] is shown in Table 14. Bruising became deeper to during the period 20 July to 5 August and WP and [DM] increased (Table 14*a*). In contrast, the period between 23 and 31 August (Table 14*b*) showed no change in [DM] with a reduction in bruise depth and an increase in WP (more flaccid tubers).

TABLE 14. DEPTH OF BRUISING (MM), DRY MATTER CONCENTRATIONS ([DM], %) AND WATER POTENTIALS (WP, BARS)

between *(a)* 20 July and 5 August and *(b)* 23 August and 31 August in Expt 1. Undefoliated, Uncut treatments only

(a)

		Date of harvest		
Variety	Irrigation regime	20 July	5 August	Difference
Bruise depth				
Lady Rosetta	Unirrigated	2.79	2.03	-0.76
	Irrigated	1.01	0.89	-0.12
Smith’s Comet	Unirrigated	4.31	4.18	-0.13
	Irrigated	4.31	2.41	-1.90
[DM]				
Lady Rosetta	Unirrigated	21.7	23.9	+2.2
	Irrigated	22.1	24.4	+2.3
Smith’s Comet	Unirrigated	23.5	26.5	+3.0
	Irrigated	23.0	25.5	+2.5
WP				
Lady Rosetta	Unirrigated	1.23	2.03	+0.80
	Irrigated	1.12	1.57	+0.45
Smith’s Comet	Unirrigated	1.46	3.49	+2.03
	Irrigated	1.24	1.84	+0.60

(b)

		Date of harvest		
Variety	Irrigation regime	23 August	31 August	Difference
Bruise depth				
Lady Rosetta	Unirrigated	3.26	2.34	-0.92
	Irrigated	3.23	3.10	-0.13
Smith’s Comet	Unirrigated	4.78	4.40	-0.38
	Irrigated	4.15	3.74	-0.41
[DM]				
Lady Rosetta	Unirrigated	24.5	24.6	+0.1
	Irrigated	24.6	24.5	–0.1
Smith’s Comet	Unirrigated	26.0	26.0	0
	Irrigated	26.1	25.9	–0.2
WP				
Lady Rosetta	Unirrigated	1.78	2.32	+0.54
	Irrigated	2.05	2.43	+0.38
Smith’s Comet	Unirrigated	1.99	2.48	+0.49
	Irrigated	1.84	2.49	+0.65

Experiment 2

There was a positive relationship between internal damage incidence and severity and tuber WP in Lady Rosetta (Figure 46*a*). There was no close relationship between blackspot incidence and WP since blackspot bruising was confined to the end of the season when variation in tuber WP was much less. There was no relationship between internal damage and WP in either Maris Piper or Smith’s Comet but in Smith’s Comet there was a close significant positive linear relationship between blackspot incidence and WP (Figure 46*b*,*c*). There was, however, a reasonably close negative exponential relationship between the incidence of cracking and WP in Smith’s Comet, which was the only variety to show significant cracking at 0.5 J impact energy (Figure 47). The exponential relationship was chosen to match the hypothetical curve produced by Smittle *et al*. (1974).

Figure 46. Relationship between internal damage incidence (■); bruise depth (□); blackspot incidence (▲) and tuber water potential in Expt 2
(a) Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet. Relationships only shown where significant. Lady Rosetta, damage incidence, $y = -1.314x^2+16.94x-0.097$, $R^2 = 0.75$; bruise depth, $y = -0.1291x^2+1.265x+1.124$, $R^2 = 0.67$. Smith's Comet, blackspot incidence, $y = 3.55x-5.83$, $R^2 = 0.83$.

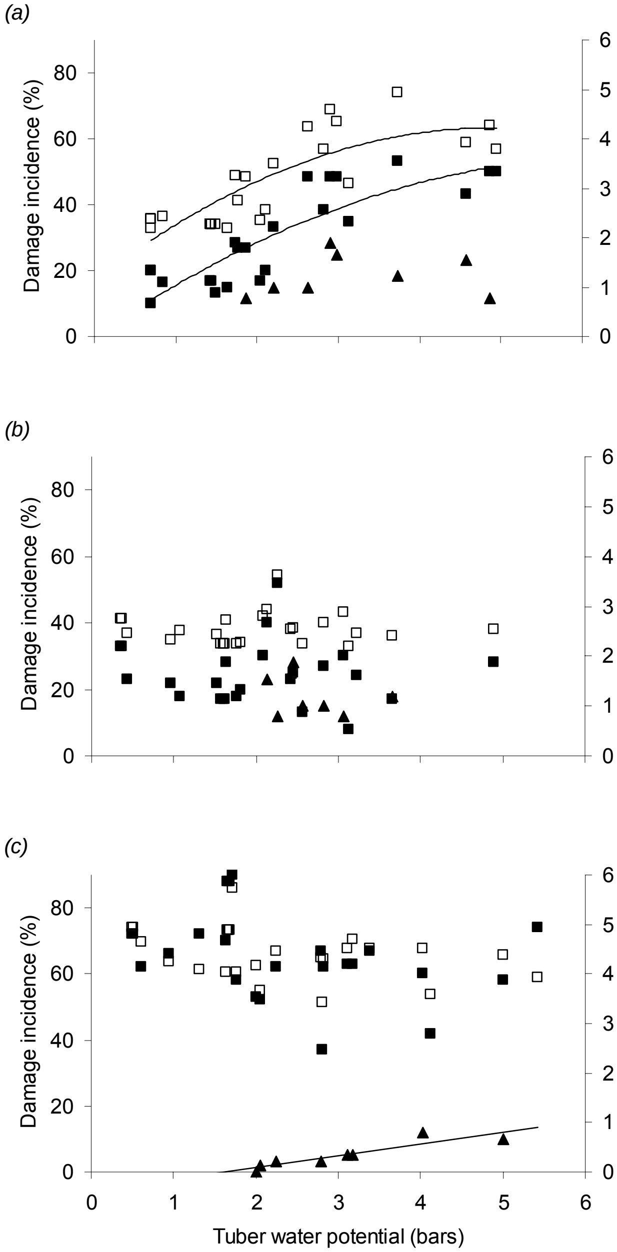
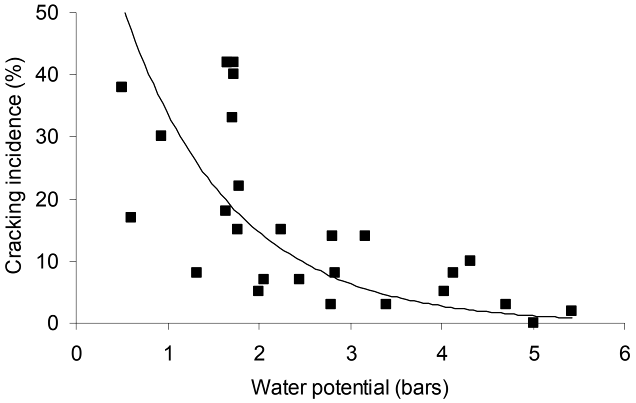


FIGURE 47. RELATIONSHIP BETWEEN CRACKING INCIDENCE AND TUBER WATER POTENTIAL IN SMITH'S COMET IN EXPT 2

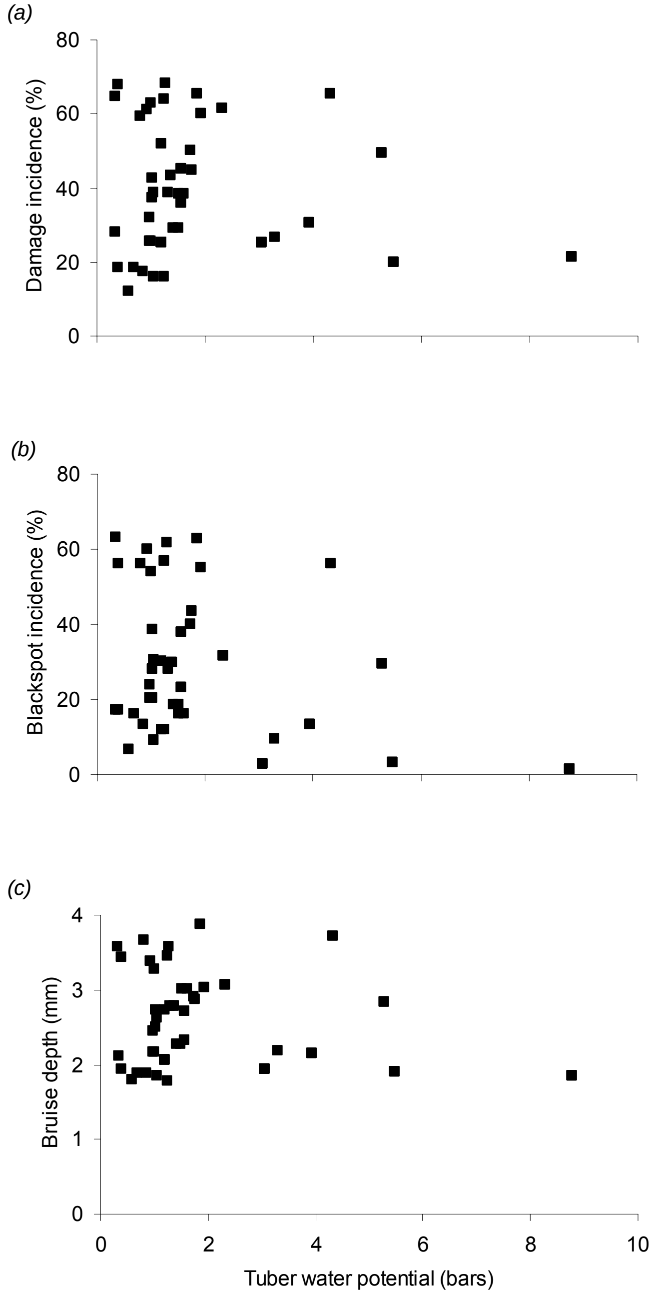
Relationship: $y = 78.08e^{-0.837x}$, $R^2 = 0.58$.



Experiment 3

There was no overall relationship between tuber bruising (internal damage, blackspot or depth of damage) and tuber WP when examining the data over the whole season (Figure 48). However, there were some significant observations. Tubers from Irrigated plots had the lowest WP (i.e. most hydrated) tubers through the season yet suffered the highest incidence of blackspot at final harvest. Blackspot bruising in Undefoliated crops generally decreased slightly or remained constant from early August until September as the weather was wet and ET demand was low to moderate. During this period, tuber WP was decreasing slowly to the lowest values measured during the season (< 1 bar). Unfortunately, tuber WP could not be measured during September as stolons had collapsed by this point but SMDs were decreasing. Tubers at this stage could be regarded as fully-hydrated. Therefore, the observation of a significant increase in bruising between the penultimate and final harvest clearly had little to do with changes in tuber WP since most stolons had senesced by this stage leaving no route for water flow into or out of tubers.

FIGURE 48. RELATIONSHIPS BETWEEN *(A)* INTERNAL DAMAGE INCIDENCE; *(B)* BLACKSPOT INCIDENCE; *(C)* DEPTH OF DAMAGE AND TUBER WATER POTENTIAL (WP) IN EXPT 3.



There were clearly changes in blackspot caused by the mechanical defoliation at the end of the Pre-dry period, regardless of whether the crops had been water-stressed (i.e. suffered a period of high SMD) prior to defoliation. Tubers from crops which were defoliated at the Pre-dry stage re-hydrated slightly faster or at the same rate as Undefoliated crops and bruising decreased. The exception was the Irrigated crop in which blackspot bruising remained high during the re-hydration phase in August despite WP decreasing to *c.* 0.34 bar. There was no evidence that tubers re-hydrated more rapidly following defoliation at the end of the Post-dry period.

Closer examination of two 6-7-day periods in August showed that when WP decreased, internal damage, blackspot and depth of bruising also decreased (Figures 49 and 50). However, whilst these data might be thought to support the hypothesis of Smittle *et al.* (1974), the magnitude of the change in bruising for a given change in WP varied considerably over time. For example, there was a large reduction (3.72 bar) in WP between 1 and 7 August for Pre-dry crops following irrigation and a decrease in blackspot incidence from 29.3 to 10.7 %, whereas between 10 and 17 August blackspot incidence decreased from 38.0 to 13.7 % in the same treatment but there was only a small decrease in WP (0.32 bar). When examining the changes in depth of bruising over the period 10-17 August, the smallest decrease in WP (Pre-dry treatment) resulted in the largest decrease in depth of bruising whilst the Unirrigated treatment rehydrated the most but showed the smallest reduction in bruise depth (Figure 50).

Figure 49. Changes in *(a)* internal damage incidence, *(b)* blackspot incidence, *(c)* bruise depth and tuber water potential (WP) during period 1-7 August in Expt 3

Unirrigated, ■; Irrigated, □; Pre-dry, ▲. Undefoliated crops only. Solid lines refer to WP, dotted lines to blackspot incidence. S.E. based on 6 D.F.

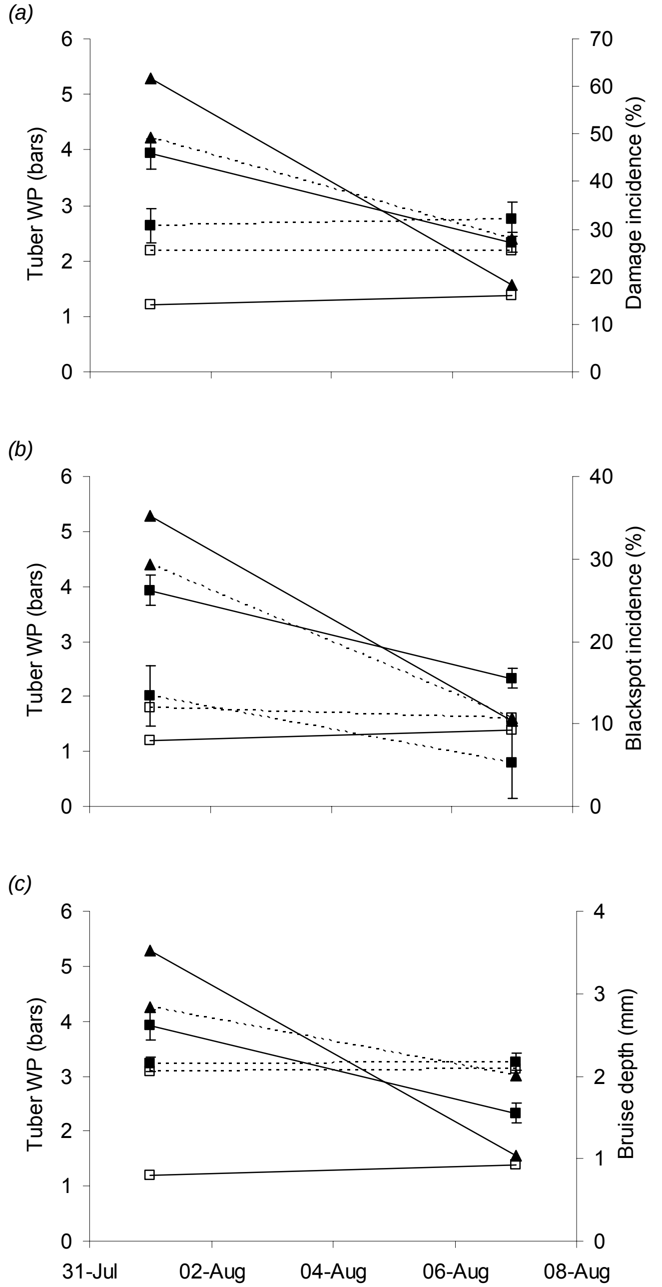
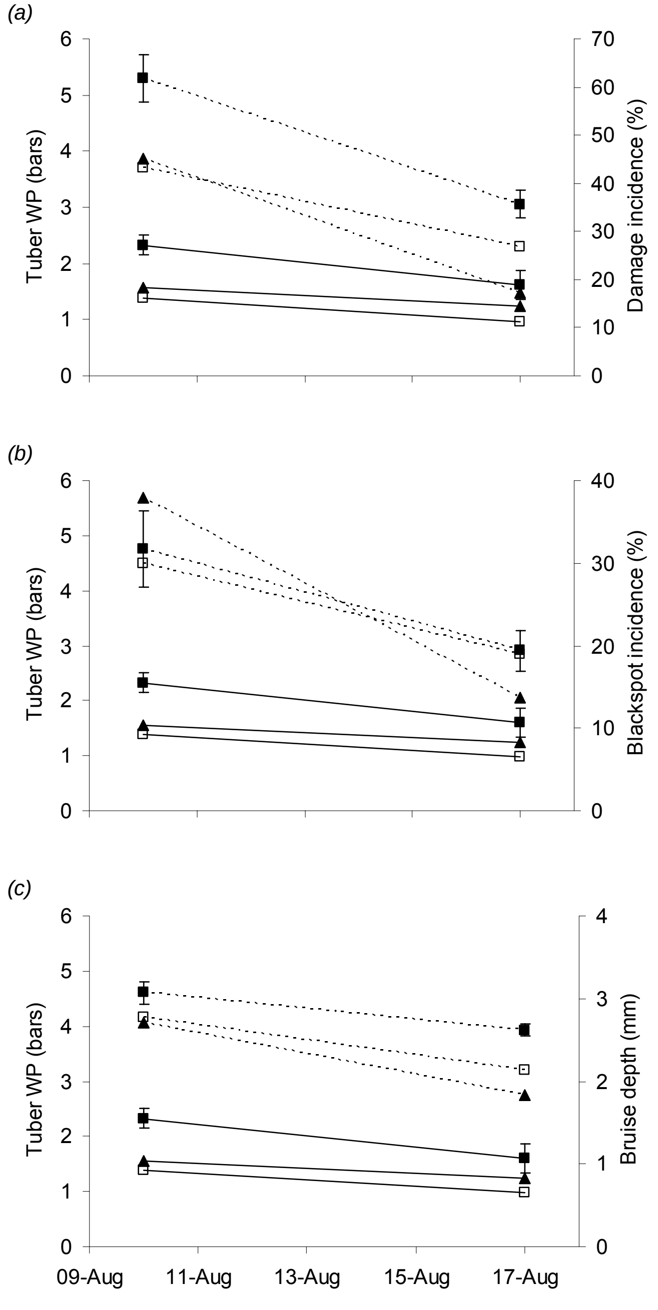


FIGURE 50. CHANGES IN *(A)* INTERNAL DAMAGE INCIDENCE, *(B)* BLACKSPOT INCIDENCE, *(C)* BRUISE DEPTH AND TUBER WATER POTENTIAL (WP) DURING PERIOD 10-17 AUGUST IN EXPT 3

Unirrigated, ■; Irrigated, □; Pre-dry, ▲. Undefoliated crops only. Solid lines refer to WP, dotted lines to blackspot incidence. S.E. based on 6 D.F.

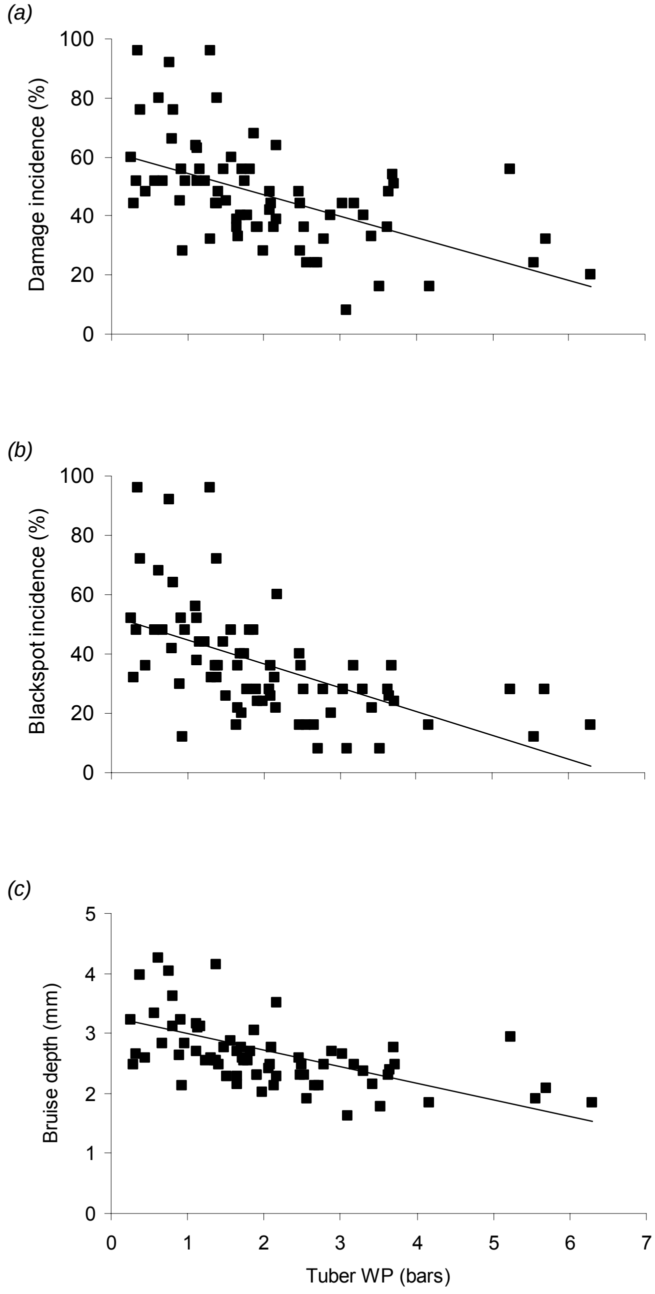


Experiment 4

In contrast with Lady Rosetta in Expt 3, there was a significant negative linear relationship between bruising and tuber WP in Maris Piper impacted at 1.0 J when the complete dataset over the whole season was examined (Figure 51). However, this does not suggest that changes in WP caused the general increase in bruising observed during the season, since there was so much variation around the fitted line. It is the direction of the change that is important, since this was contrary to the expected hypothesis that as turgor decreases, blackspot worsens. Restricting the dataset to 18 September, the relationship was much improved, with over 60 %

of the variation in bruising accounted for by changes in water WP but there was a limited range of WP and the tubers were fairly turgid by this stage (0.34-1.99 bars). The accuracy with which blackspot bruising could be predicted from tuber WP worsened as the measurements were made earlier in the season such that no significant relationship existed in July and early August.

FIGURE 51. RELATIONSHIPS BETWEEN *(A)* INTERNAL DAMAGE INCIDENCE; *(B)* BLACKSPOT INCIDENCE; *(C)* DEPTH OF DAMAGE AND TUBER WATER POTENTIAL (WP) IN EXPT 4
Relationships: *(a)* $y = -7.31x+61.9$, $R^2 = 0.29$; *(b)* $y = -8.04x+52.9$, $R^2 = 0.30$; *(c)* $y = -0.275x+3.27$, $R^2 = 0.26$.
300 kg N/ha treatments only.



Experiment 5

In previous years, there was found to be no overall relationship between blackspot incidence and tuber WP when examining the data over the whole season but reasonably close relationships had been found between internal damage and WP in Lady Rosetta. In order to test the hypothesis that blackspot bruising worsens as tubers dehydrate, measurements of bruising and WP were taken from frequent sequential harvests (2 hourly intervals) and these produced some important observations.

Unirrigated and Irrigated crops started 2 August with SMDs of 41 and 9 mm, respectively, and the day had a low potential evapotranspiration (ET_0 2.23 mm). Tuber WP increased from 1.5 to 3 bars in Unirrigated crops and 0.7 to 1.2 bars in Irrigated between 08:00 and 10:00 h when it was sunny (Figure 52*a*). The radiation intensity gradually decreased until 13:00 h and WP barely changed in both crops over the same period. It began to become brighter and hotter again after 13:00 h and tuber WP started to increase again, particularly in Unirrigated crops. Internal damage tended to decrease between 08:00 and 10:00 h in both Unirrigated and Irrigated crops (Figure 52*b*). It remained stable in Unirrigated crops until 14:00 h when it increased again. In fully-irrigated crops, however, it increased continually between 10:00 and 16:00 h. Blackspot incidence did not change throughout the day in Unirrigated crops, except after 16:00 h when it increased sharply (Figure 52*b*). In irrigated crops, blackspot incidence increased progressively from 12:00 h. The volume of the blackspot bruises increased throughout the day in both crops (Figure 52*c*) but in Unirrigated crops the bruises became deeper as well as wider, whereas in Irrigated they only became wider as the day progressed.

On 13 August, ET_0 was slightly above average (3.56 mm) and there was a much more typical pattern of radiation distribution during the day than 2 August. However, the canopies of the Post-dry treatments investigated on 13 August were in an advanced stage of senescence (*c.* 20 % ground cover). There was a much reduced demand for water on the plants and tuber WP only increased by a small amount during the day (1.21 to 1.87 bars) but changes in WP closely reflected the changes in bruising (Figure *b*). There was an increase in internal damage and blackspot bruising between 12:00 and 16:00 h (Figure *a*) when WP increased most rapidly. The blackspot bruising increased in severity (as measured by bruise volume) as a consequence of bruises increasing in width during the day whilst the depth of bruising remained constant (Figure *b*).

FIGURE 52. CHANGES IN BRUISING AND WATER POTENTIAL DURING THE DAY ON 2 AUGUST IN EXPT 5
(a) tuber water potential (WP)*; (b)* internal damage and blackspot bruising incidence; *(c)* blackspot volume. Internal damage incidence, ■; blackspot incidence, ▲. Closed symbols, Unirrigated; Open symbols, Irrigated.

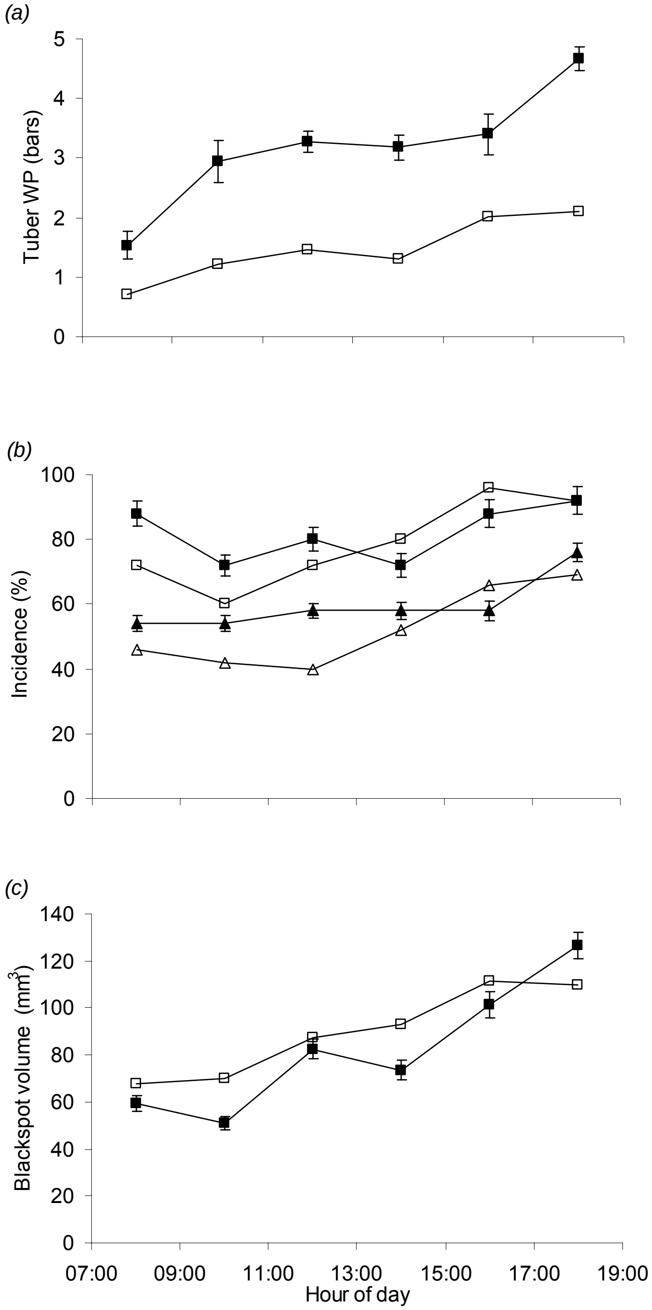
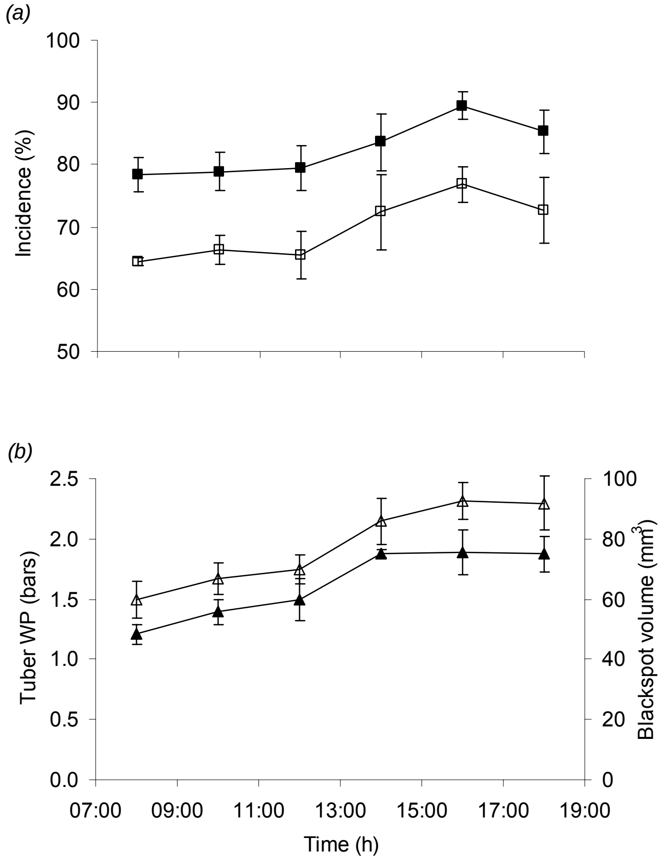


Figure 53 Changes in bruising and water potential during the day on 13 August in the undefoliated Post-dry treatment in Expt 5

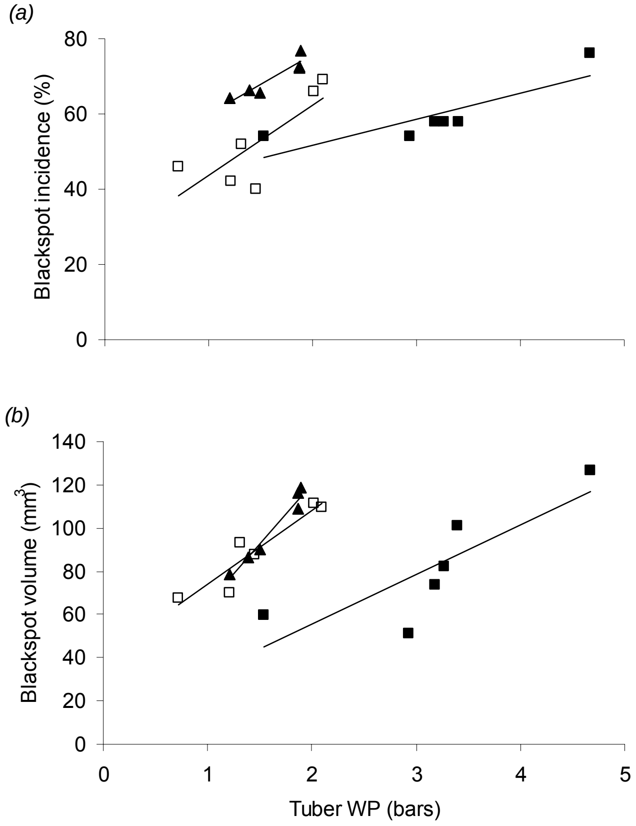
(a) Internal damage and blackspot bruising incidence; *(b)* tuber water potential (WP) and blackspot volume. Internal damage incidence, ■; blackspot incidence, □; water potential, ▲; blackspot volume, △.



The relationships between blackspot bruising and tuber WP for the two days when frequent measurements were taken are shown in Figure 54. Whilst the relationships were fairly close-fitting ($R^2 = 0.68$-0.89), it is clear that there were different slopes for different irrigation treatments, even on the same day. Therefore, it seems that any relationship between bruising and tuber turgor may be conditioned by the water regimes experienced prior to that point in the season. So whilst the hypothesis that blackspot bruising increases as tubers dehydrate (Smittle *et al*. 1974) may hold directionally, it cannot be used predictively or absolutely to determine how a crop will bruise.

Figure 54. Relationships between *(a)* blackspot incidence; *(b)* blackspot volume and tuber water potential (WP) in Expt 5

2 August, Unirrigated, ■; 2 August, Irrigated, □; 13 August, Post-dry, ▲. Relationships: *(a)* ■, $y = 6.84x+38.0$, $R^2 = 0.70$; □, $y = 18.86x+24.8$, $R^2 = 0.63$; ▲$y = 15.85x+44.0$, $R^2 = 0.85$; *(b)* ■, $y = 23.0x+9.5$, $R^2 = 0.68$; □, $y = 33.7x+40.5$, $R^2 = 0.87$; ▲, $y = 56.1x+8.7$, $R^2 = 0.96$.



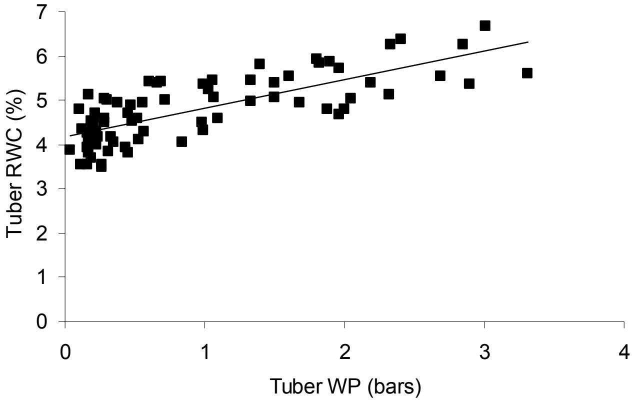
Relationship between bruising and tuber Relative Water Content (RWC)

Experiment 6

In Expt 6, tuber RWC measurements were taken during August and September to assess an alternative to tuber WP in the prediction of bruising, particularly during the period when stolon senescence prevented measurement of WP.

There was only a moderate correlation between tuber RWC and WP (Figure 55). Data from Expt 5 also showed a poor correlation between these two variables and it is clear that the measurements are not interchangeable, an observation also made by Hole *et al.* (1997).

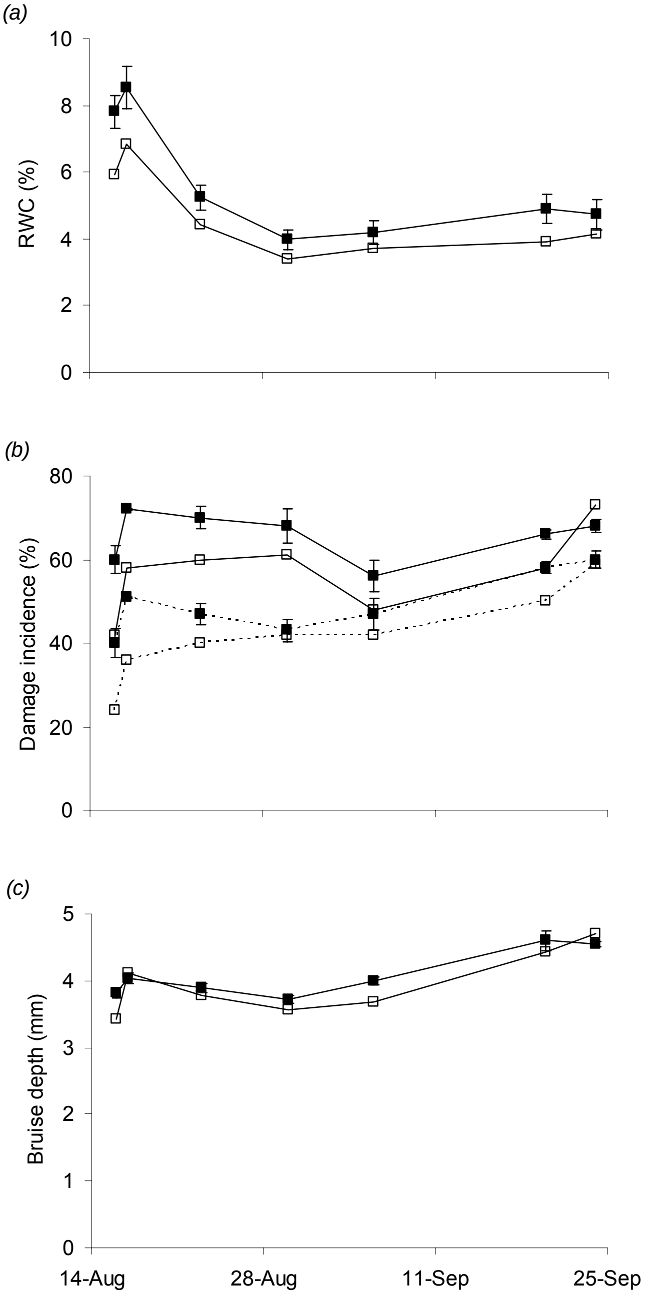
FIGURE 55. RELATIONSHIP BETWEEN TUBER RELATIVE WATER CONTENT (RWC) AND TUBER WATER POTENTIAL (WP) IN EXPT 6
Cultivated Dry, N150 treatments only. Relationship: y = 0.642x + 4.18, R^2 = 0.56.



The patterns of internal damage, blackspot incidence and bruise depth broadly mirrored the changes in RWC, with Unirrigated crops bruising more severely and having a higher RWC than Irrigated (Figure). However, the indices of bruising at any particular RWC were not constant and so the changes in RWC over time did not result in consistent changes in the magnitude of bruising.

FIGURE 56. *(A)* TUBER RELATIVE WATER CONTENT (RWC), *(B)* INTERNAL DAMAGE AND BLACKSPOT INCIDENCE AND *(C)* BRUISE DEPTH IN EXPT 6

Unirrigated, ■; Irrigated, □. Solids lines in *(b)*, internal damage; dotted lines, blackspot. Cultivated-Dry, N150 treatments only. S.E. based on 9-24 D.F.

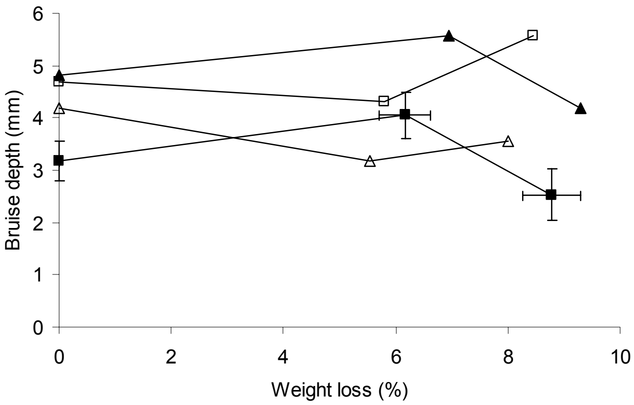


Drying

Experiment 1

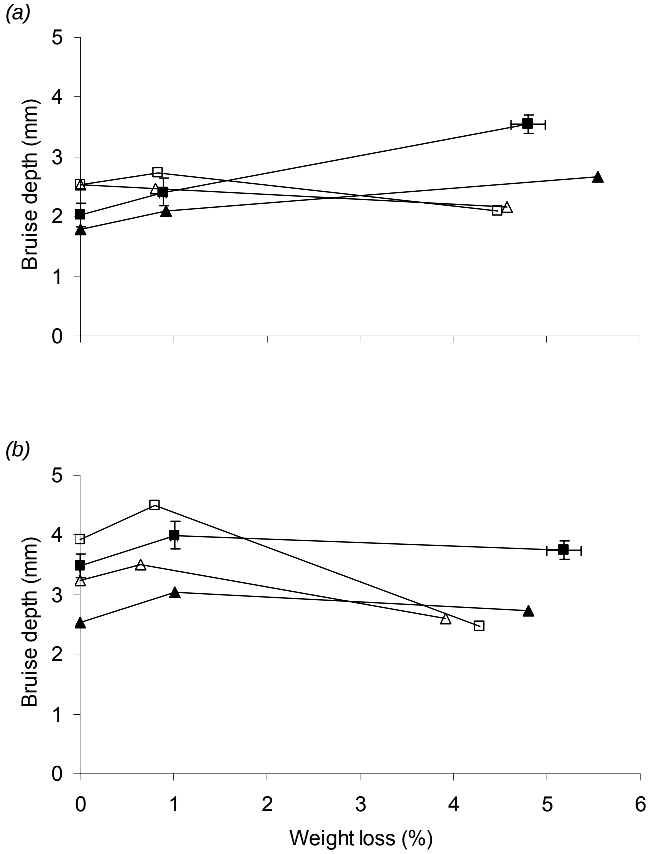
On three occasions, tubers were placed under controlled conditions of constant temperature and with or without fan ventilation which caused them to lose water vapour and therefore turgor. Exposing tubers to drying conditions in the laboratory immediately after harvest caused changes in bruising. On 27 July, water loss was rapid through unset skins under forced ventilation (*c.* 5-6 % in 40 hours) and depth of bruising initially tended to increase in Unirrigated tubers of both Lady Rosetta and Smith's Comet but reduce in Irrigated tubers (Figure). The slightly greater the water loss of the Unirrigated tubers compared with Irrigated may have been a consequence of a smaller average tuber size in Unirrigated crops leading to greater surface area : volume ratio. The increased bruising with initial drying was mainly confined to increases in blackspot with a complete elimination of shatter cracking in Smith's Comet. With further water loss (*c.* 8-9 % total), bruising improved in Unirrigated crops to return to values numerically slightly lower than observed prior to drying. Conversely, bruising worsened in Irrigated crops as weight loss increased from *c.* 5-8 %.

FIGURE 57 EFFECT OF WEIGHT LOSS ON BRUISING SEVERITY IN EXPT 1 ON 27 JULY
Lady Rosetta, ■; Smith's Comet, ▲. Unirrigated, closed symbols; Irrigated, open symbols. Uncut treatments only. S.E. based on 12 D.F.



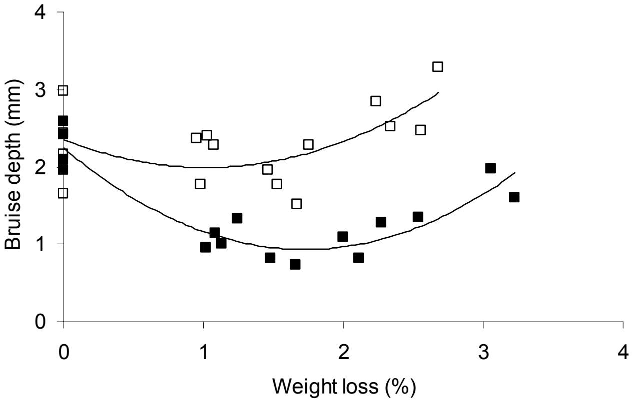
On 13 August, in Lady Rosetta there was an increase in bruising severity in Undefoliated crops as weight loss increased but little change in bruising severity with weight loss in Defoliated crops (Figure 58*a*). In contrast, there was an increase in bruise depth in Smith's Comet with a small weight loss of *c.* 1 %. Further weight loss to 4-5 % did not change bruising severity in Undefoliated crops but it reduced bruising depth in Defoliated crops (Figure 58*b*).

FIGURE 58. EFFECT OF WEIGHT LOSS ON BRUISING SEVERITY IN EXPT 1 ON 13 AUGUST
(a) Lady Rosetta; *(b)* Smith's Comet. Unirrigated, Undefoliated, ■; Unirrigated, Defoliated, □; Irrigated, Undefoliated, ▲; Irrigated, Defoliated, △. Uncut treatments only. S.E. based on 12 D.F.



Where water loss was much slower owing to tubers having set skins and not using forced ventilation (21 September), a water loss of 1-2 % reduced mean bruising depth from 2.4 to 1.0 mm (Figure). Water loss of *c.* 3 % resulted in similar severity of bruising to freshly-harvested tubers.

FIGURE 59. RELATIONSHIP BETWEEN BRUISE DEPTH AND WEIGHT LOSS ON DRYING ON 21 SEPTEMBER IN EXPT 1
Lady Rosetta (■); Smith's Comet (□). Relationships: Lady Rosetta, $y = 0.440x^2 - 1.519x + 2.24$, $R^2 = 0.86$; Smith's Comet, $y = 0.349x^2 - 0.711x + 2.35$, $R^2 = 0.38$.



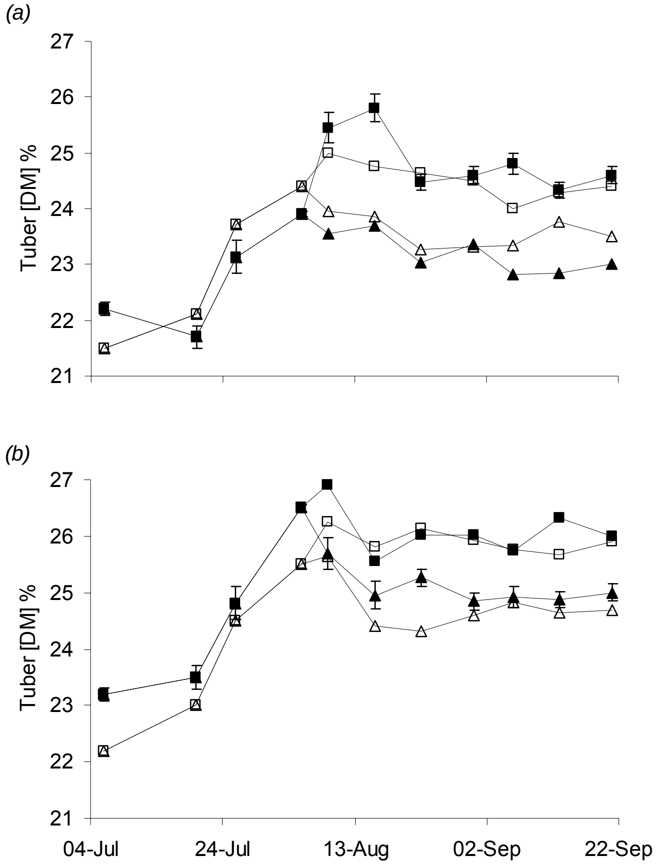
Clearly, the results of the earliest test show that immature tubers rapidly lose water which can cause them to change their susceptibility to blackspot bruising but different husbandry treatments can alter the bruising response to drying. Varieties which crack on impact (e.g. Smith's Comet) would be rendered more resilient to this form of physical damage following slight dehydration. The last drying test suggests that there may be an optimum hydration status of tubers for bruising and that windrowing tubers for a short period could make them less susceptible to bruising if the tubers were in a turgid state prior to harvest. These drying data seem to contradict the data on bruising WP when tubers lose water during the day via their stolon rather than through the periderm.

Dry Matter concentration

Experiment 1

Tuber [DM] was higher in Smith's Comet than Lady Rosetta, reaching a peak of 27 % in Unirrigated plots in early August. Despite the application of 205 mm of water in Irrigated crops by this stage, [DM] was only 0.5-0.6 % lower than Unirrigated and the differences in [DM] between irrigation regimes were not significant for most of August and September (Figure).

FIGURE 60. TUBER DRY MATTER CONCENTRATIONS [DM] IN EXPT 1
(a) Lady Rosetta; *(b)* Smith's Comet. Unirrigated, Undefoliated, ■; Unirrigated, Defoliated, ▲; Irrigated, Undefoliated, □; Irrigated, Defoliated, △. S.E. based on 12 or 28 D.F.



Tuber [DM] decreased following defoliation but continued to increase in Undefoliated crops. Within one week of defoliation, there was a difference in [DM] of 1.3 % between Defoliated and Undefoliated crops in Lady Rosetta which was maintained until final harvest. In Smith's Comet, the directional and temporal effect was the same but the magnitude of the difference was smaller (1.1 %) than in Lady Rosetta. The decrease in [DM] in Unirrigated crops following rainfall in early August was greater in Undefoliated than in Defoliated crops, indicating that defoliation caused rapid root death which prevented uptake of water by tubers.

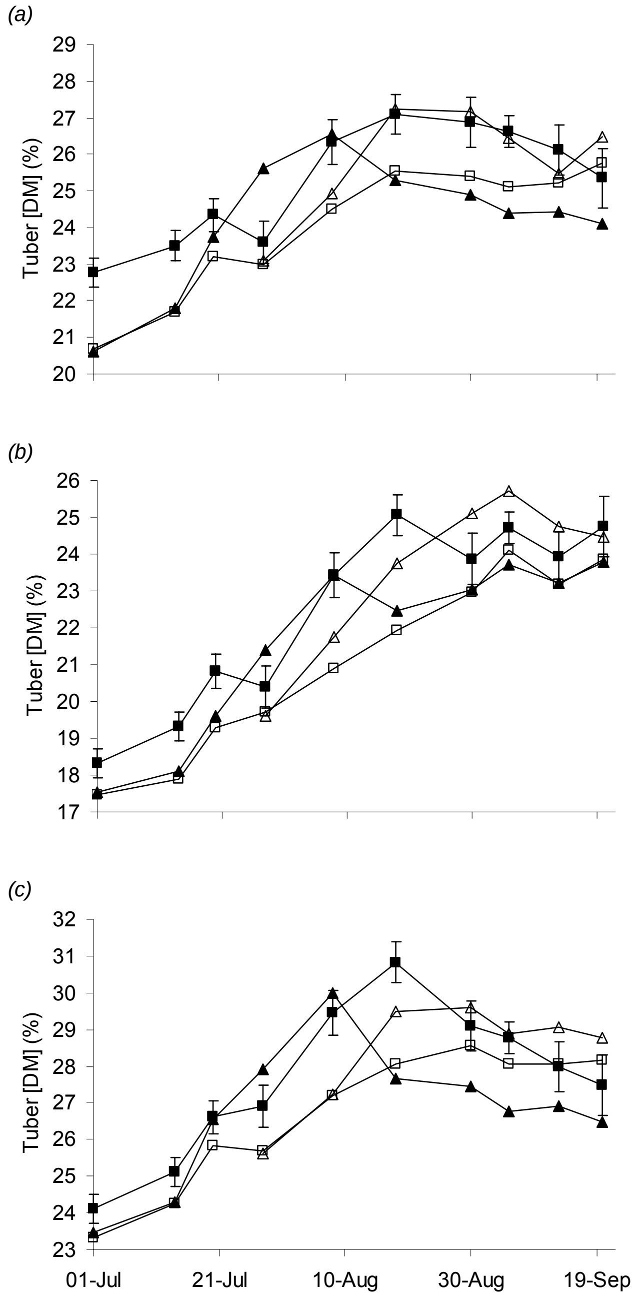
Experiment 2

Tuber [DM] was high for all varieties, particularly in Smith's Comet but Maris Piper was slower to increase, reaching a maximum around 5 September, whereas Lady Rosetta and Smith's Comet attained their peaks on 18 August (Figure). When sampling started at the beginning of July, Unirrigated crops had higher tuber [DM] than Irrigated crops, particularly in Lady Rosetta. Soon after the onset of drought in the Pre-dry treatments, however, [DM] rapidly increased to the concentration in Unirrigated plots until irrigation was applied to alleviate the water stress. In Lady Rosetta and Smith's Comet, the re-hydration of Pre-dry plots caused [DM] to decrease continually for the rest of the season and be maintained at a lower level than other treatments (Figure *a*,*c*). In Pre-dry Maris Piper, however, there was an initial decrease in [DM] over the first 10 days of re-hydration but then [DM] continued to increase for the rest of the season (Figure *b*). At final harvest, Pre-dry treatments had significantly lower [DM] than other plots in Lady Rosetta and Smith's Comet but there was no significant difference between the irrigation treatments imposed on Maris Piper. In the Post-dry treatments, [DM] increased in Lady Rosetta and Smith's Comet during the drought stress period but, in contrast with Pre-dry treatments, hardly changed during re-hydration (Figure *a*,*c*), most probably because the crops died rapidly during the re-hydration, preventing the roots taking up water.

The [DM] of Unirrigated Lady Rosetta and Smith's Comet decreased continually from the beginning of September, falling 1.6 % in 3 weeks as a consequence of 82 mm of rain in two events on 5 and 9 September. However, [DM] in Unirrigated Maris Piper did not respond to this large amount of rainfall. All Irrigated, Pre- and Post-dry crops received 24 mm of irrigation on 2 September which caused [DM] to decrease slightly but the heavy rain had no effect in altering [DM]. In Maris Piper, [DM] fell slightly after the rain in early September but increased again thereafter. Maris Piper had more ground cover during this period than Lady Rosetta and Smith's Comet, which had senesced appreciably by the end of August (Figure 8) and probably had little active root in the upper soil profiles to facilitate re-hydration.

Figure 61 Tuber dry matter concentrations in Expt 2

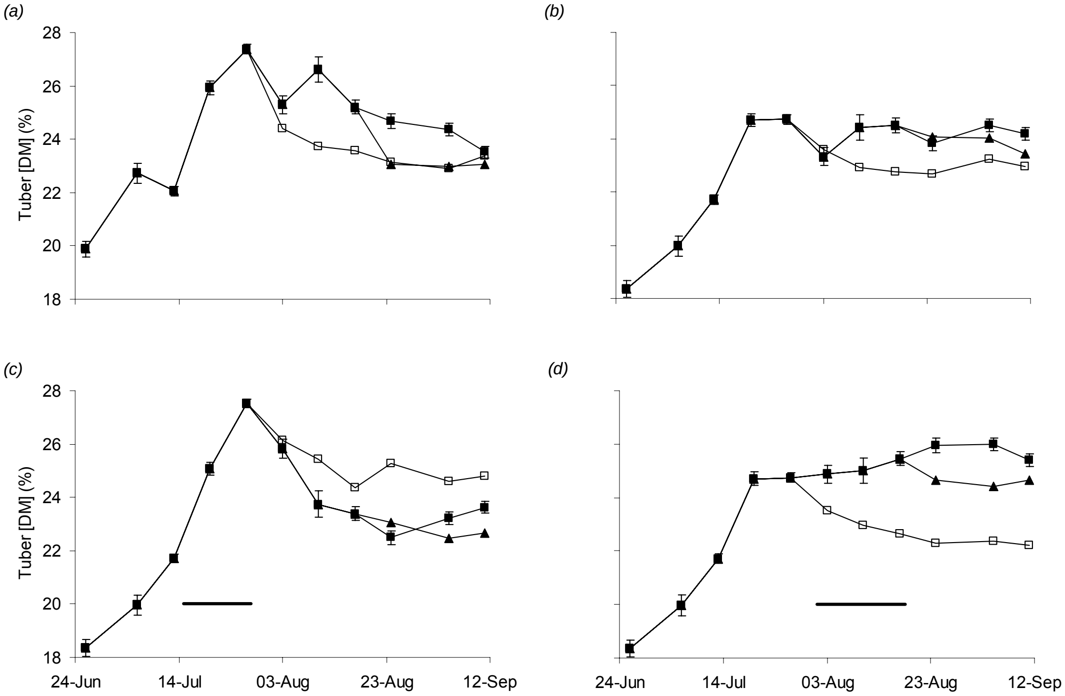
(a) Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet. Unirrigated, ■; Irrigated, □; Pre-dry, ▲; Post-dry, △. S.E. based on 12 or 16 D.F.



Experiment 3

Tuber [DM] increased quickly during July reaching > 27 % in Unirrigated and Pre-dry treatments and *c.* 25 % in fully irrigated plots despite the SMD being maintained < 27 mm (Figure). Rain and the onset of cooler weather at the end of July caused [DM] to decrease over the next 2 weeks. Thereafter, [DM] remained approximately constant until the end of the season. By mid-September, tuber [DM] was similar for all irrigation treatments. Defoliation at the end of the Pre-dry period (28 July) decreased [DM] in all irrigation treatments compared with Undefoliated or Post-dry defoliation, except for the Pre-dry treatment where [DM] in Pre-dry defoliated crops remained significantly higher than other defoliation regimes. Defoliating at the end of the Post-dry period (18 August) when senescence had commenced had little effect on [DM] compared with not defoliating.

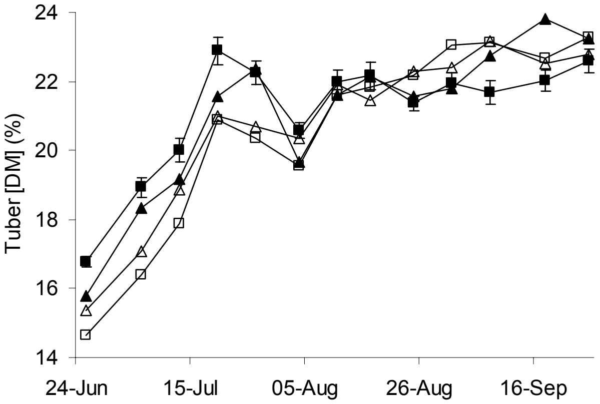
FIGURE 62. TUBER DRY MATTER CONCENTRATION [DM] IN EXPT 3
(a) Unirrigated; *(b)* Irrigated; *(c)* Pre-dry; *(d)* Post-dry. Undefoliated, ■; Defoliated Pre-dry, □; Defoliated Post-dry, ▲. Bar marks period of water restriction in Pre- and Post-dry irrigation treatments. S.E. based on 4 or 22 D.F.



Experiment 4

Tuber [DM] was increased by withholding irrigation throughout June and July. Thereafter, there was no significant difference in [DM] between any treatment, including rate of nitrogen (Figure).

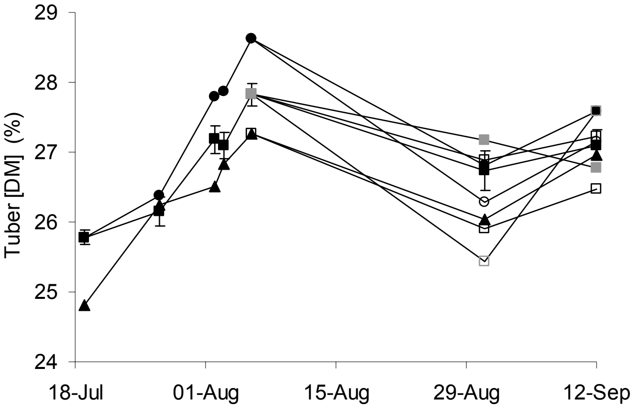
FIGURE 63. TUBER DRY MATTER CONCENTRATION IN EXPT 4
Cult Dry, Unirrigated, ■; Cult Dry, Irrigated, □; Cult Wet, Unirrigated, ▲; Cult Wet, Irrigated, △. 300 kg N/ha treatments only. S.E. based on 6 D.F.



Experiment 5

When sampling began on 19 July, Unirrigated crops had a higher tuber [DM] than Irrigated but thereafter there was no significant difference between these two treatments (Figure). At the time of defoliation, Pre-dry crops had a significantly higher tuber [DM] than fully irrigated but this difference was eroded during senescence.

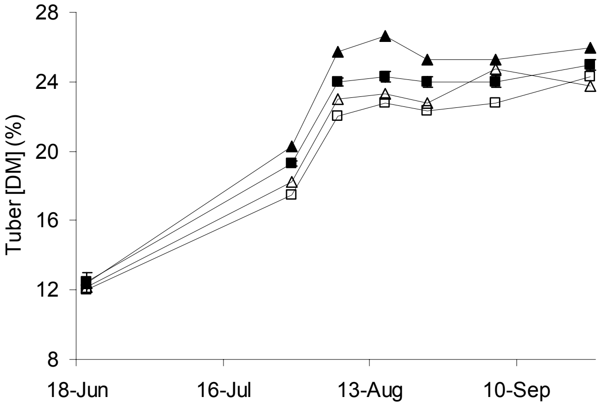
FIGURE 64. TUBER DRY MATTER CONCENTRATION IN EXPT 5
Unirrigated, ■; Irrigated, ▲; Pre-dry, ●; Post-dry, ■. Closed symbols, Undefoliated, open symbols, Defoliated. S.E. based on 6 or 21 D.F.



Experiment 6

The effect of cultivating wet or dry soil, irrigation and N supply on tuber [DM] are shown in Figure . At the first harvest, [DM] was not affected by any treatment or combination of treatments. At subsequent harvests, [DM] concentration was lower in Cult Dry and Irrigated plots. Increasing the amount of nitrogen applied to the crop resulted in a systematic decrease in [DM] (data not shown).

FIGURE 65. TUBER DRY MATTER CONCENTRATION [DM] IN EXPT 6
Cult Dry, Unirrigated, ■; Cult Dry, Irrigated, □; Cult Wet, Unirrigated, ▲; Cult Wet, Irrigated, △. 150 kg N/ha treatments only. S.E. based on 6 D.F.



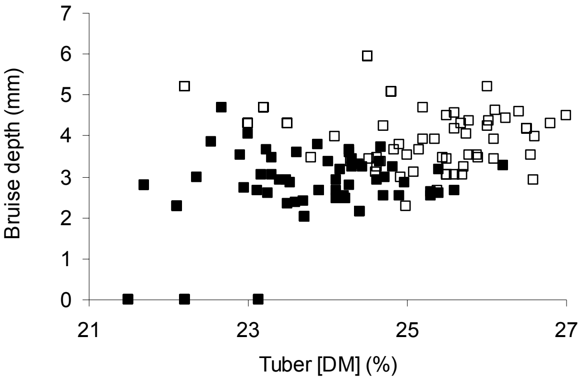
Relationship between bruising and dry matter concentration

Experiment 1

Within a variety, there was no significant correlation between bruise score and tuber [DM], either at individual harvests or over the course of the season (Figure). This might be expected to be the case since although the water content of tubers must also alter with changes in tuber [DM], this need not represent a change in turgidity of the tubers. Changes in either of these variables appeared not to be mediated through the other. Any relationships between bruising and [DM] are probably dependent on the manner in which a change in [DM] is achieved. Changing it via deliberate alteration of tuber WP is quite a different process from that achieved as a consequence of assimilate accumulation during normal growth. Since [DM] generally stabilized from mid-August in all treatments, there were obviously other factors associated with bruising since severity of bruising increased significantly during September when [DM] remained stable.

FIGURE 66. BRUISING SEVERITY VERSUS TUBER DRY MATTER CONCENTRATION [DM] (TREATMENT MEANS FOR ALL HARVESTS) IN EXPT 1

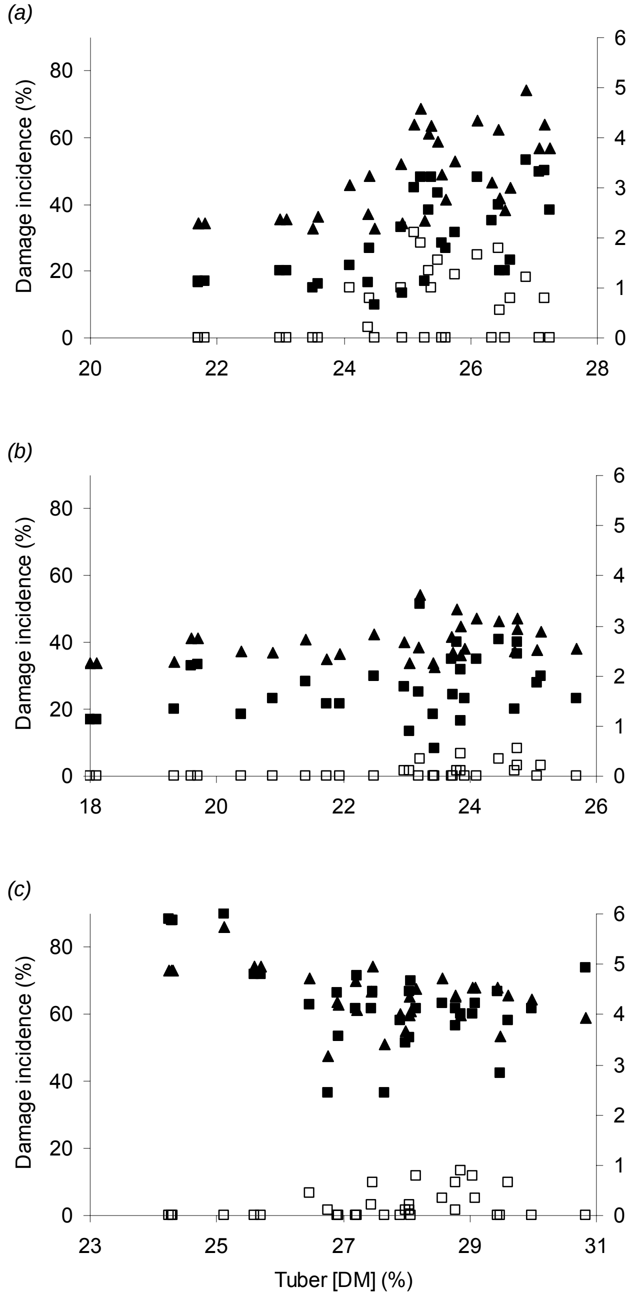
Lady Rosetta, ■; Smith's Comet, □.



Experiment 2

Within a variety, there were no significant relationships between damage incidence, damage severity or blackspot incidence and tuber [DM] that could be regarded as causal, either at individual harvests or over the course of the season (Figure). This is in agreement with the findings from Expt 1. This might be expected to be the case, since although the water content of tubers must also alter with changes in tuber [DM], this need not represent a change in turgidity of the tubers. Changes in either of these variables appeared not to be mediated through the other. Any relationships between bruising and [DM] are probably dependent on the manner in which a change in [DM] is achieved. Changing it via deliberate alteration of tuber WP is a different process from that achieved as a consequence of assimilate accumulation during normal growth.

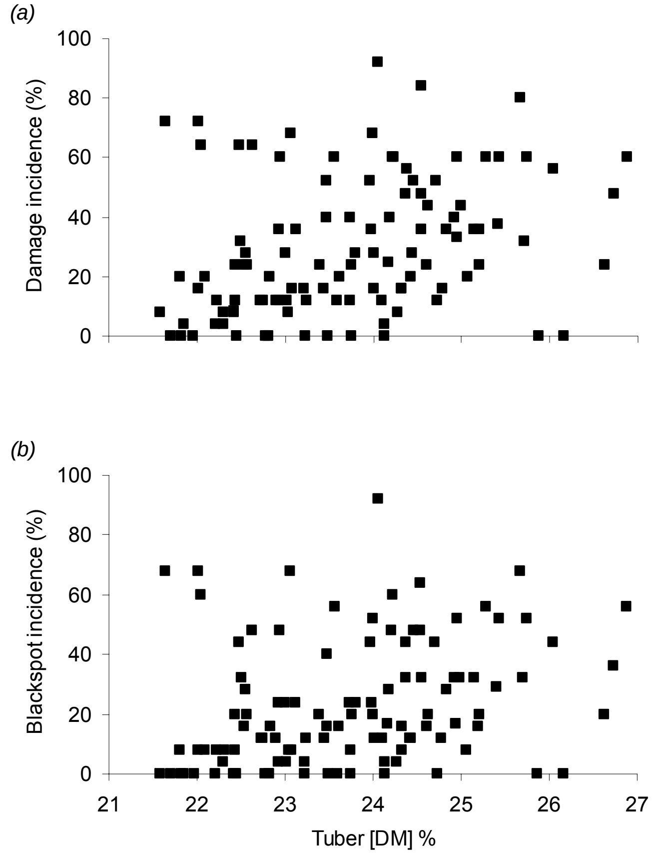
FIGURE 67 RELATIONSHIP BETWEEN INTERNAL DAMAGE INCIDENCE, ■, BLACKSPOT INCIDENCE, □, BRUISE DEPTH, ▲ AND TUBER DRY MATTER CONCENTRATION, [DM] IN EXPT 2
(treatment means for all harvests). *(a)* Lady Rosetta; *(b)* Maris Piper; *(c)* Smith's Comet.



Experiment 3

Similar to Expts 1 and 2, there was no relationship in Lady Rosetta between internal damage or blackspot incidence and tuber [DM] either at final harvest or throughout the season (Figure).

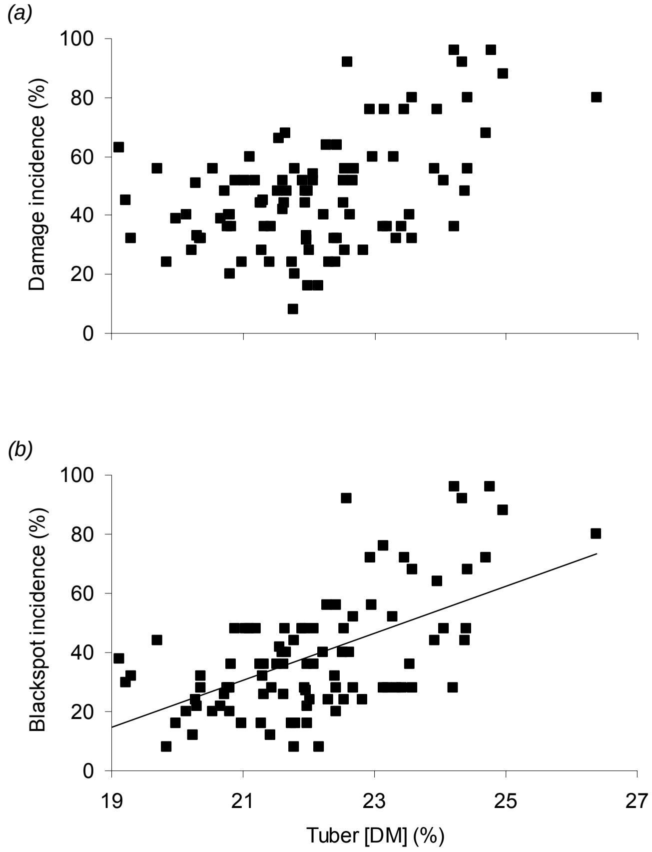
Figure 68. Relationship between bruising and tuber dry matter concentration [DM]
(a) Internal damage incidence; *(b)* blackspot incidence.



Experiment 4

In contrast with Expt 3, there was a significant positive linear relationship between blackspot incidence and tuber [DM] when combining the data from all harvests and treatments but the degree of variation in bruising accounted for by changes in tuber [DM] was low and therefore [DM] cannot be implicated as a major causal factor in bruising in Maris Piper (Figure). There was no significant relationship between internal damage incidence and tuber [DM] (Figure *a*).

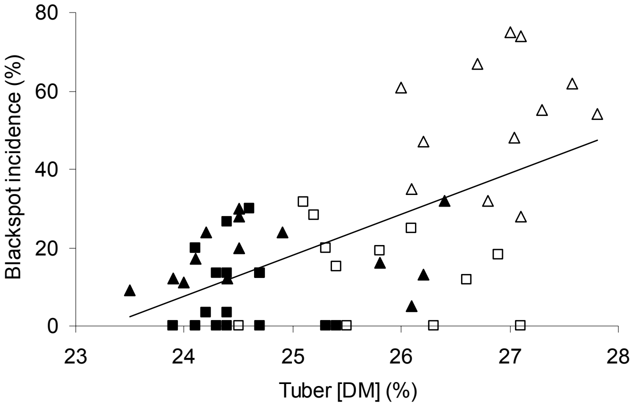
FIGURE 69. RELATIONSHIP BETWEEN BRUISING AND TUBER DRY MATTER CONCENTRATION [DM] IN EXPT 4
(a) Internal damage incidence; *(b)* blackspot incidence. Relationship: *(b)* y = 7.98x−137, R^2 = 0.32.



Experiment 5

Similar to Expts1-3, there was no relationship between blackspot incidence and tuber [DM], either at final harvest or throughout the season. Although plotting all the data for common Unirrigated and Irrigated treatments across Expts 1-3 and 5 produced a significant positive linear relationship between blackspot incidence and tuber [DM], there was no relationship that could be regarded as causal as the variation in prediction of bruising was large (Figure). Tuber [DM] was high in all treatments in Expt 5 but in Expt 2, tubers with a [DM] of 26-27 % had a blackspot incidence of 0-25 % whereas in Expt 5 the same [DM] produced blackspot incidences of 28-75 %.

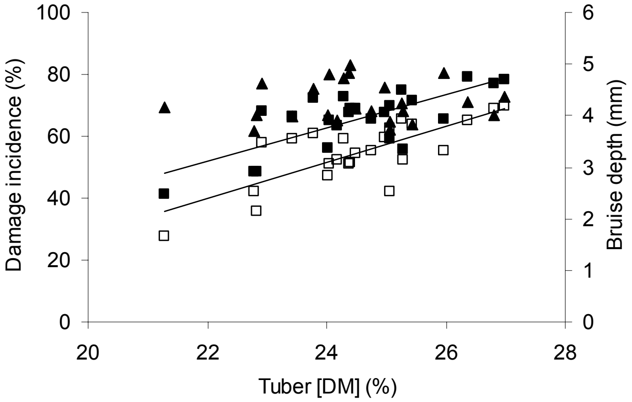
FIGURE 70. RELATIONSHIP BETWEEN BLACKSPOT BRUISING INCIDENCE AND TUBER DRY MATTER CONCENTRATION [DM]
Expt 1, ■; Expt 2, □; Expt 3, ▲; Expt 5, △. Overall relationship: y = 10.4x–244, R^2 = 0.35. Means of Unirrigated and Irrigated treatments only.



Experiment 6

There were significant positive linear correlations between internal damage incidence and blackspot incidence and tuber [DM] when examined over the whole sampling period (Figure). The degree of fit of the relationships gave more confidence than Expt 4 that differences in [DM] may be implicated in differences in bruising. There was no correlation between bruise depth and [DM].

FIGURE 71. RELATIONSHIP BETWEEN BRUISING AND TUBER DRY MATTER CONCENTRATION [DM] IN EXPT 6.
Relationships: internal damage incidence, ■, 5.32x − 65.0, R^2 = 0.53; blackspot incidence, □, 5.77x − 89.9, R^2 = 0.56; bruise depth. ▲ (relationship not significant).



Tuber yields

Experiment 1

Irrigation had no significant effect on fresh weight yields but the GC in Unirrigated crops was maintained much longer than for Irrigated crops (Figure 7) which balanced the advantage in GC gained by irrigating during the early part of the season (Table 15). *Erwinia* infection during late July caused Irrigated Lady Rosetta to lose GC rapidly but no plants with blackleg symptoms were observed in Unirrigated Lady Rosetta or any Smith's Comet. Mechanical defoliation on 6 August reduced yield slightly (Table 15).

TABLE 15. TUBER FRESH WEIGHT YIELDS (T/HA) AT FINAL HARVEST (13 SEPTEMBER) IN EXPT 1

	Unirrigated		Irrigated	
	Undefoliated	Defoliated	Undefoliated	Defoliated
Lady Rosetta	57.7	51.8	59.4	57.3
Smith's Comet	50.3	45.3	53.6	50.4
S.E. (28 D.F.)		2.36		
(S.E.for same irrig)		(2.30)		

Experiment 2

Tuber fresh weight yields were lowest in the Unirrigated plots but there was a much greater effect of with-holding irrigation completely in Smith's Comet than the other two varieties (Table 16). In Lady Rosetta and Smith's Comet, removing irrigation during a hot period in August at the onset of senescence caused significant leaf death and reduced light interception capacity, which in turn reduced yields and had a much greater effect than a 3-week drought period starting in mid-July where temperatures and evaporative demand were much lower. Indeed, in these two varieties, Unirrigated and Post-dry treatments produced the same fresh weight yields even though the Post-dry treatments received 195 mm of irrigation. This seems to contradict the GC data, where Unirrigated Lady Rosetta and Smith's Comet had significantly lower GC than the Post-dry treatment for much of the season (Figure 9). However, the tuber DM yields were higher for Post-dry crops than for Unirrigated, especially in Smith's Comet (data not shown). Unirrigated crops also had a slower rate of senescence than Post-dry crops which contributed to the small differences in yield. Restricting water supply to Maris Piper during July or August had no effect on tuber fresh weight yield.

TABLE 16. TUBER FRESH WEIGHT YIELDS (T/HA) AT FINAL HARVEST (20 SEPTEMBER) IN EXPT 2

	Variety		
Irrigation treatment	Lady Rosetta	Maris Piper	Smith's Comet
Unirrigated	52.7	56.6	39.4
Irrigated	58.3	66.1	50.7
Pre-dry	58.6	62.5	48.3
Post-dry	51.9	66.9	42.7
S.E. (for same irrigation treatment), 16 D.F.		2.45 (2.11)	

Experiment 3

There was no effect of irrigation or defoliation regime on the total number of tubers produced (490 000 ± 21 300/ha). Tuber fresh weight yields were lowest in the Unirrigated plots and restricting irrigation during the Pre-dry period also caused a significant reduction (Table 17). There was no significant effect on yield caused by the Post-dry restriction period. Defoliating early (end of the Pre-dry period) reduced yield very significantly but the crops had commenced the rapid senescence phase at the timing of the Post-dry defoliation and although there was a significant loss of leaf area duration, tuber yields were less affected by this defoliation.

TABLE 17. TUBER FRESH WEIGHT YIELDS (T/HA) AT FINAL HARVEST (11 SEPTEMBER) IN EXPT 3

	Defoliation regime		
Irrigation treatment	Undefoliated	Defoliated Pre-dry	Defoliated Post-dry
Unirrigated	49.8	32.0	45.3
Irrigated	67.5	46.6	51.3
Pre-dry	56.4	36.5	52.6
Post-dry	60.1	42.7	57.4
S.E. (22 D.F.)		3.42	

Experiment 4

Cultivating soil whilst wet (46.9 t/ha) reduced tuber yield by almost as much (10.3 t/ha) as withholding irrigation completely (12.2 t/ha; Table 18). Rate of nitrogen fertilizer had no significant effect on yield, with the optimum being < *c.* 100 kg N/ha.

TABLE 18. TUBER FRESH WEIGHT YIELDS (T/HA) AT FINAL HARVEST (11 SEPTEMBER) IN EXPT 4

		Nitrogen fertilizer application (kg N/ha)				
Cultivation	Irrigation	0	100	200	300	Mean
Cult Dry	Unirrigated	49.6	47.7	53.2	49.3	50.0
Cult Dry	Irrigated	67.1	67.7	60.6	62.1	64.4
Cult Wet	Unirrigated	38.3	45.9	41.1	42.0	41.8
Cult Wet	Irrigated	46.7	55.7	47.4	57.7	51.9
S.E. (24 D.F.)			2.31			4.15
S.E. (same Cult x Irrig)			3.26			

Experiment 5

Fully-irrigated yield was 50.2 t/ha but withholding irrigation and rainfall for 3 weeks prior to the onset of senescence reduced total FW yield at final harvest (44.7 ± 1.44 t/ha) as much as withholding irrigation completely (44.1 t/ha). Eliminating all inputs of water post-senescence reduced yields slightly but not significantly (47.8 t/ha). Defoliation had no significant effect on yield probably because natural senescence was so rapid in undefoliated crops. Tuber [DM] was high but unaffected by the contrasting irrigation and defoliation regimes.

Experiment 6

Tuber yields were increased significantly by irrigation during August and September and the overall response to irrigation at final harvest was *c.* 14 t FW/ha (Table 19). Unlike Expt 4, cultivating the soil whilst wet had no effect on yield, probably because the soil dried too rapidly between the pre-irrigation event and cultivating. At the final harvest, the largest yield resulted from applying 300 kg N/ha. Since the experiment tested only three nitrogen rates the optimum nitrogen application rate cannot be defined with any certainty, however it is probably between 150 and 300 kg N/ha. For comparison, in Expt 4 there was no response to nitrogen fertilizer.

TABLE 19. MAIN EFFECTS OF CULTIVATION, IRRIGATION AND N APPLICATION RATE ON TUBER FW YIELD (T/HA) ON FOUR SAMPLING OCCASIONS IN EXPT 6

	Date of harvest			
	20 June	19 July	24 August	24 September
Cult Dry	1.0	22.0	47.2	58.1
Cult Wet	1.3	22.3	47.4	58.0
Unirrigated	1.0	21.2	42.8	51.0
Irrigated	1.2	23.1	51.7	65.1
0 kg N/ha	1.4	18.0	38.6	46.8
150 kg N/ha	1.4	25.5	51.2	59.8
300 kg N/ha	0.6	22.9	52.0	67.6
Mean	1.1	22.1	47.3	58.1
S.E. (6 D.F.) Cult or Irrig.	0.10	0.54	1.07	1.23
S.E. (24 D.F.) N rate	0.17	0.73	1.31	1.26

4. Conclusions

Tuber [DM], turgor and the general water status of tubers are generally accepted as being of importance in determining the frequency of bruising but without sufficient understanding to allow preventative management. Although the water content of tubers must also alter with changes in tuber [DM], this need not represent a change in turgidity of the tubers. Changes in either of these variables are not necessarily mediated through the other. For this reason, it is not surprising that there was no overall relationship between bruising and tuber [DM] in any experiment in the project that could be regarded as causal, even though there was a significant positive correlation between bruising and [DM] in Expts 4 and 5. Any relationships between bruising and tuber [DM] are probably dependent on the manner in which a change in DM is achieved. Changing [DM] via deliberate alteration of tuber water status (WP) is a different process from that resulting from assimilate accumulation during normal growth.

The research programme aimed to establish the relationships between susceptibility to bruising and tuber WP and test the hypothesis of Smittle *et al.* (1974) that blackspot bruising worsens and cracking improves as tubers become more flaccid. Changes in tuber WP may influence two of the physical parameters (tissue strength and elasticity) that affect bruising. However, there was no clear evidence that the WP of the tubers during the season was the major controlling factor in bruise susceptibility during the commercial harvesting window.

Fully-irrigated crops had the lowest SMD and lowest tuber WP throughout the season yet still bruised and in Expt 3 they bruised considerably worse at final harvest than Unirrigated crops. Crops bruised badly in some experiments even though tubers were maintained in a hydrated state for most of the season in fully-irrigated crops with the exception of short periods when ET demand was high. In all seasons, wherever SMDs reached 50-60 mm in Unirrigated crops or those that had temporary water stress imposed during mid-season, these crops exhibited worse bruising at that time than fully-irrigated crops but by full senescence this transitory difference no longer existed. By final harvest, in most experiments with the exception of Expt 3, bruising was the same for Unirrigated or Irrigated crops, irrespective of what had happened earlier in the season.

However, there were changes in the type of damage between harvests that reflected changes in tuber WP. In Expt 1, when tubers were very turgid (low WP), substantial shatter cracking was observed in Smith's Comet which was reduced as WP increased. As tubers became more flaccid the bruising type changed to blackspot but only later in the season. There was also a close negative relationship between cracking and WP in Smith's Comet in Expt 2 and cracking could be reduced by maintaining higher SMDs late in the season without incurring a significant yield penalty.

The progressive increase in blackspot bruising from early August to the end of September that occurred irrespective of changes in WP or [DM] in most experiments could be due to (a) increased permeability of the membranes separating the enzyme and substrate, (b) an increase in the concentration of either tyrosine or enzyme over this period or (c) changes in the mechanical properties of the cells unrelated to WP. There were periods in Expt 1 (e.g. 20 July to 5 August) when WP increased significantly but bruising decreased. The most severe bruising in Smith's Comet was on 26 July in Irrigated crops when WP was lowest (most hydrated). There was a 40 % incidence of bruising in these crops but only 3 % cracking at this stage whereas there was a 20 % incidence of cracking on 6 July when tubers were only moderately hydrated. The change in the resilience of the periderm as the skin sets could have an influence on energy dissipation within the tuber and the type of bruise which occurs.

In Expt 2, internal damage could be predicted from measurements of tuber WP with reasonable accuracy in Lady Rosetta but not in Maris Piper or Smith's Comet. Sufficient changes in WP to influence bruising occurred during short periods (e.g. 3-4 days) of drying but large changes in tuber WP induced by prolonged drying took time to correct. Tuber re-hydration depended on (a) the stage of crop growth (there was slow re-hydration if the crop was moderately to severely senesced), (b) absolute SMD and evaporative demand at time of re-wetting and (c) probably also the evaporative demand experienced by crop earlier in the season. Tubers did not fully re-hydrate if exposed to high evaporative stress around onset of senescence and it took more than one single 15-18 mm irrigation event to re-hydrate tubers in such a state. This observation makes it difficult to predict the effect of pre-defoliation irrigation on bruising. In many cases growers may be irrigating at this time under the belief that tubers will re-hydrate quickly before root death occurs and make tubers less sensitive to bruising. It seems that the evidence from experiments where irrigation was scheduled in different ways prior to the onset of senescence (and where measurements of tuber re-hydration were taken) does not support the commonly-held view that pre-defoliation irrigation will cause a reduction in bruising 2-4 weeks after defoliation through hydration of tubers.

There was a large increase in bruising in Expt 3 between 11 and 22 September in all treatments. This could be an indication that tissues were becoming mechanically weaker as the crop reached an advanced stage of foliage senescence. Mean soil temperatures were very consistent during September, varying between 16.8 and 18.8 °C for the period 11-22 September and tubers were harvested at 18 °C on both occasions and were impacted at 20 °C in the laboratory. These temperatures were common throughout all experiments. Therefore, changes in tuber temperature cannot be implicated in the large increases in bruising observed. Bruises became deeper as well as more numerous during September indicating that (a) the forces of impact were penetrating further into the peri-medullary zone and/or (b) internal tissues were becoming weaker during this period. It is believed that the intensity of colour development of blackspot bruises may be more closely related to the number of cells crushed rather than the concentration of tyrosine in each cell (Lærke *et al*. 2002). In this series of experiments, blackspot bruises did not change in colour over the period close to harvest but almost certainly more cells were involved in the damage. Bruises became deeper as the season progressed but their width stabilized once senescence had commenced. In Expt 2, however, internal damage decreased significantly between the last two harvests in September, so the observations were not universal.

From examining the data over all four years of the project, there does not appear to be a consistent pattern in changes in internal damage susceptibility during the season. Initially, blackspot was absent and internal damage was confined to leakage of cell contents rather than an enzymatic reaction between PPO and tyrosine. The substrates for melanin formation were presumably either (a) absent or (b) present in such low concentration for no significant colorimetric reaction to develop during the early part of the season. After the initial appearance of blackspot bruises (which varied in the Lady Rosetta experiments by *c*. 6 weeks from similar emergence dates), whitespot bruising tended to decrease as a proportion of internal damage suggesting that colorimetric reactions were taking place at sites where earlier in the season there was insufficient substrate (PPO concentration being assumed as non-limiting).

Bruising was considerably worse in 2007 (e.g. 75-80 % blackspot incidence at final harvest in Expt 5) than in any other season in the project even in tubers which were maintained in a hydrated state for most of the season in fully-irrigated plots. Blackspot bruising in Maris Piper was worse in Expt 6 (60 % incidence, 4.6 mm depth) than in Expt 4 (45 % incidence, 2.9 mm) despite halving the impact energy from 1.0 J to 0.5 J. Blackspot bruising became evident much earlier in 2007, in mid-July in Expt 5 rather than mid-August in Expts 1and 2. However, whitespot incidence in Lady Rosetta in mid-July was much higher in Expt 5 (37 %) than in Expt 1 (10 %) or Expt 2 (20 %) suggesting that cells were also weaker in Expt 5 as well as having an earlier accumulation of tyrosine.

The generally inexorable increase in blackspot bruising within a particular season in terms of developing the biochemical enzyme-substrate reaction components obviously will alter any relationship that exists between blackspot bruising and WP unless the time interval between measurements are short enough to account for any drift in biochemical apparatus. Closer examination of hydration status over short time periods holds the key to testing the hypothesis that changes in hydration status affect susceptibility to bruising through changes in the strength and elasticity of tuber tissue. Two consecutive 7-day periods in Expt 3 during August showed that the directional changes in WP were reflected in similar directional changes in bruising (which supports the original hypothesis) but the magnitude of the change in bruising varied over time. The intensive sampling of tuber and leaf WP in Expt 3 demonstrated that changes in WP almost equivalent to the range encountered across the season could occur within one day if the ET demand was great and the tubers started the day in a hydrated status. This diurnal change in tuber WP will alter the rheological and physical condition of tubers and most probably bruising susceptibility without the confounding influence of long time periods between samples which may alter other factors responsible for bruising.

Experiments 3 and 5 showed that dehydration of tubers during hot days was sufficient to increase bruising from commercially-acceptable levels in the morning to unacceptable by late afternoon and it could still increase significantly on cooler days and even with sparse crop cover creating a low evaporative demand on the plant. The magnitude of the changes in tuber WP (and therefore bruising) during drying periods was often greater in fully-irrigated than in droughted crops since there was a greater potential for the tuber to dehydrate. The limited data taken close to final harvest also indicated that crops seemed to reach an equilibrium WP during mid-September irrespective of the irrigation regime imposed on them earlier in the season. In Expts 1 and 2, the final tuber WP was 2.1-2.4 bars but it was much lower in Expt 3 (1.03 bars) and Expt 5 (1.5 bars). As seen by the variation in blackspot incidence at final harvest from year-to-year, the suggestion of an equilibrium WP at full senescence indicates that measurements of tuber WP of senescent crops close to harvest are unlikely to predict likely bruise susceptibility.

There was convincing evidence that mechanically defoliating a crop just prior to the onset of senescence during a period of hot weather and high evapotranspiration demand increased the severity of blackspot bruising compared with crops allowed to senesce naturally, irrespective of the SMD at the time of defoliation. This effect appeared to be totally unrelated to changes in tuber WP and the differences were apparent only a few days after defoliation in Expts 3 and 5 but were still evident 6 weeks later. In Expt 1, the effect was confined to Unirrigated Lady Rosetta and the difference in blackspot incidence became progressively worse post-defoliation and was highly significant at final harvest. Irrigated crops did not exhibit the effect. However, in Expt 3, the increase in blackspot incidence after defoliation was greater in crops that had received irrigation during the season than Unirrigated. In Expt 3, there was also a smaller, but still significant, effect from delaying defoliation until the end of the Post-dry period if the crop had been deprived of water in the previous three weeks. An interesting observation in this experiment was that crops which had been irrigated prior to defoliation at the end of the Pre-dry stress period had zero foliage regrowth from cut stems whereas Unirrigated plots defoliated at this time had to be re-trimmed with secateurs on three occasions. This indicates that there was still some meristem activity in Unirrigated crops and could explain why there was a smaller difference in bruising between Pre-dry Defoliated and Undefoliated crops at the end of the season than in Irrigated crops.

The effect of defoliation might be biochemical, i.e. the ‘stress’ of defoliation might increase the tyrosine concentration in cells at the impact site and therefore increase the potential to exhibit a blackspot bruise reaction. It is generally accepted that larger bruises result from the rupture of the internal membranes of more cells rather than an increased biochemical potential (Lærke *et al*. 2002). Therefore, the data from Expt 5 suggest that there is a major mechanical contribution to tissue resilience since bruises became universally wider and mostly deeper in defoliated crops, rather than becoming darker in colour (which would suggest an increase in the tyrosine available for reaction). It is not possible, however, to infer that a slower chemical defoliation might reduce or eliminate the effects, since this was not tested.

In summary, the relationships between blackspot bruising incidence and severity and tuber WP move in the direction proposed in the hypothesis proposed by Smittle *et al*. (1974). Over short time periods (e.g. < 7 days), the relationships had reasonable fit but had different slopes for contrasting irrigation regimes and at different points in the season. Therefore, no one unifying relationship was found since there were different relationships for different varieties as well as irrigation regimes. It seems is not possible measure the WP of a tuber (or its turgor) and predict how it will bruise (a) at that moment, or (b) in the future but clearly this project has demonstrated that tuber turgidity can play a major role in blackspot bruising. It is difficult to manipulate turgor controllably without incurring a yield penalty though it is possible to predict tuber WP closely from SMDs based on Penman-Monteith evapotranspiration models (Stalham & Allen 2004). There was conclusive evidence that mechanically defoliating crops with close to full canopy cover on hot days could increase bruising compared with leaving crops to senesce naturally. The lack of consistency between irrigation regimes of the magnitude of the effect of defoliation on bruising does not indicate that pre-defoliation irrigation would reduce the incidence of bruising by changing the hydration status of tubers but the avoidance of defoliation during hot period would be more successful.

5. References

ALLEN, R. G., PEREIRA, L. S., RAES, D. & SMITH, M. (1998). Crop evapotranspiration – guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper 56*. Rome: FAO.

BAJEMA, R. W., HYDE, G. M. & BARITELLE, A. L. (1998). Turgor and temperature effects on dynamic failure properties of potato tuber tissue. *Transactions of the American Society of Agricultural Engineers* **41**, 741-746.

BPC (2004). *BPC National Bruising Survey*. Oxford: British Potato Council, 25 p.

BURSTALL, L. & HARRIS, P. M. (1983). The estimation of percentage light interception from leaf area index and percentage ground cover in potatoes. *Journal of Agricultural Science, Cambridge* **100**, 241-244.

FELLOWS, J. (2004). *Factors associated with internal damage and bruising in potato tubers*. Project Report 807/227. Oxford: British Potato Council. 49p.

FINNEY, E. E. & FINDLEN, H. (1967). Influence of preharvest treatments upon turgor of Katahdin potatoes. *American Potato Journa*l **44**, 383-386.

GANDAR, P. W. & TANNER, C. B. (1976). Leaf growth, tuber growth, and water potential in potatoes. *Crop Science* **16**, 534-538.

HOLE, C. C., MCGARRY, A, DREW, R. L. K., PARSONS, N. R., FOWLER, J. F. & STALHAM, M. A. (1997). Improving quality by minimising damage. *Final Report Project No. 807/148*. Oxford: British Potato Council.

KRAMER, P. J. (1969). *Plant and soil water relationships: a modern synthesis*. New York: McGraw-Hill, pp. 347-360.

LÆRKE, P. E., CHRISTIANSEN, J. & VEIERSKOV, B. (2002). Colour of blackspot bruises in potato tubers during growth and storage compared to their discolouration potential. *Postharvest Biology and Technology* **26**, 99-111.

PAYNE, R. W., BAIRD, D. B., CHERRY, M., GILMOUR, A. R., HARDING, S. A., KANE, A. F., LANE, P. W., MURRAY, D. A., SOUTAR, D. M., THOMPSON, R., TODD, A. D., TUNNICLIFFE WILSON, G., WEBSTER, R. & WELHAM, S. J. (2002). *Genstat™ Release 6.1 Reference Manual*. Oxford: Clarendon Press.

REEVE, R. M., TIMM, H. & WEAVER, M. L. (1971). Cell size in Russet Burbank potato tubers with various levels of nitrogen and soil moisture tensions. *American Potato Journal* **48**, 450-456.

SMITTLE, D. A, THORNTON, R. E., PETERSON, C. L. & DEAN, B. B. (1974). Harvesting potatoes with minimum damage. *American Potato Journal* **51**, 152-164.

STALHAM, M. A. & ALLEN, E. J. (2004). Water uptake in the potato (*Solanum tuberosum*) crop. *Journal of Agricultural Science, Cambridge* **142**, 1-21.

STALHAM, M. A., ALLEN, E. J., ROSENFELD, A. B. & HERRY, F. X. (2007). Effects of soil compaction in potato (*Solanum tuberosum*) crops. *Journal of Agricultural Science, Cambridge* **145**, 295-312.

STARK, J. C. & HALDERSON, J. L. (1987). Measurement of diurnal changes in potato tuber growth. *American Potato Journal* **64**, 245-248.