PT004

Potato irrigation - development of irrigation scheduling guidelines

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HAL

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PT004

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POTATO IRRIGATION - DEVELOPMENT OF IRRIGATION SCHEDULING GUIDELINES

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1.0 PROJECT EXECUTIVE SUMMARY

This 3 year project began in 1989 in response to demand from both the fresh and processing sectors of the Western Australian potato industry for increased yields of higher quality potatoes. There was general recognition that irrigation management played a vital role in determining both of these factors, but the relative irrigation requirements of commonly grown varieties had not been adequately defined. Irrigation scheduling techniques had been developed overseas for a number of varieties based on optimum available soil moisture levels for different crop growth stages. No such techniques had been studied in Western Australia (WA) and it was believed that significant losses were being incurred by growers through the effects on yield and quality of suspected over-irrigation, poor timeliness of irrigation events, and possible leaching of fertilisers from the crop root zone.

The aims of the project were to (1) conduct a preliminary examination of the operating efficiency of commonly used irrigation systems in the Manjimup-Pemberton area of Western Australia and provide recommendations for system improvement where necessary, and (2) develop irrigation scheduling guidelines for important potato varieties, based on the use of simple soil moisture monitoring techniques, that would enable growers to maximise tuber yield and quality, and water use efficiency.

A survey of irrigation practices in eight representative commercial crops during the 1989/90 season showed that growers were using mostly fixed irrigation cycles and this resulted in crops being both over and under watered at varying times during their growth. The degree of over-watering was not high, averaging ~6% over the entire crop growth period. Of greater concern was the tendency to supply inadequate amounts of water to crops, particularly during the important early to mid tuber bulking period between 60 and 100 days after planting. These problems highlighted the need for development and use of more precise irrigation scheduling techniques.

In the 1990/91 season, a survey of the set-up and management of irrigation systems in the Manjimup-Pemberton area revealed that low sprinkler operating pressure was the most common cause of poor irrigation uniformity within the most commonly used semi-permanent sprinkler irrigation systems . Low operating pressure was, in turn, most commonly caused by having too many sprinklers along each lateral line. Simple pressure loss calculations can be performed to determine the optimum number of sprinklers per lateral (based on a maximum allowable pressure variation of 5%), and these calculations should be carried out before irrigation systems are installed in each new paddock.

Field experiments were used to examine the yield and tuber quality response of Delaware, Cadima, Kennebec and Russet Burbank potatoes to varying levels of soil moisture during different crop growth stages. For Delaware, WA's most common fresh market variety, it was found that to maximise both yield and the proportion of Premium grade tubers, the available soil moisture level should be maintained above 80% during the period between emergence and early tuber growth. This soil moisture level corresponded with a soil water potential (SWP), measured using tensiometers installed at 30cm depth, of between -20 and -25 kPa. High yields and tuber quality were achieved by maintaining this high soil moisture regime throughout all crop growth stages. However, provided adequate soil moisture levels were maintained between emergence and tuber growth, it was found that the available soil moisture level could be allowed to fall to as low as 65% (SWP -60kPa) during later growth stages without impacting significantly on tuber yield or quality. If such low soil moisture levels were allowed to develop between emergence and early tuber growth then yield and tuber quality were reduced. In the soil type used in these studies (loamy sand), up to 55mm of water was required to return the profile to field capacity when the available soil moisture level fell to 65%. Applying this amount of water in a single application to crops grown on the sloping paddocks common to the Manjimup-Pemberton area may cause soil erosion problems. For this reason, it is recommended that the available soil moisture level not be allowed to fall below 75% (SWP -35kPa) at any growth stage in Delaware potatoes.

As with Delaware, it was found that high yields and acceptable tuber quality in Cadima and Kennebec potatoes could be achieved by maintaining the available soil moisture level above 80% (SWP -25 kPa) during all growth stages. However, the yield and quality of Cadima and Kennebec were not reduced when the available soil moisture level was allowed to fall to 72% (SWP -40 kPa) during all growth stages. This suggests that, compared with Delaware, Cadima and Kennebec may be more tolerant to low soil moisture levels during early growth stages. Further work is needed to more accurately define the irrigation requirements of Cadima and Kennebec during each crop growth stage.

On the sandy loam soils used for Russet Burbank irrigation studies in this project, regardless of the irrigation regime imposed, the yield of this variety was found to be strongly linearly related to the total amount of crop water use(CWU), up to 610mm (CWU = soil moisture content at emergence - soil moisture content at harvest + irrigation + rainfall). However, while total water applied, and hence CWU, appeared to be a dominant factor determining the yield and quality of Russet Burbank potatoes, like Delaware, Russet Burbank was found to be sensitive to low soil moisture levels in the period between emergence and early tuber growth. For maximum yield and optimum tuber quality, where quality was measured in terms of tuber shape, specific gravity and the level of internal defects, the results of studies in this project suggest that the SWP in Russet Burbank crops (measured at 30cm depth) should be maintained above -20kPa during this early growth period. During later growth periods, allowing the SWP to decline to -40kPa had no effect on tuber yield or quality.

In a single field experiment with Russet Burbank potatoes planted in mid November on a sandy loam soil type, no significant interaction was found between irrigation level (up to 125% estimated evapotranspiration) and nitrogen level (up to 600 kg N/ha). The optimum total nitrogen application level was found to be between 335 and 375 kg N/ha. Further work is required to determine whether such nitrogen levels are appropriate for other planting times, varieties and soil types. Also, the possible significant interaction between nitrogen and irrigation levels on sandier soil types than that used here deserves further investigation.

Tensiometers were used for the measurement of soil water potential in most of the crop water requirement studies in this project. We found them to be simple to install and monitor, and when properly maintained, they gave reliable readings of soil water potential that can be used for accurate irrigation scheduling in potato crops. However, other devices are commonly used for monitoring soil moisture and thus irrigation scheduling in potato crops. One such device is the neutron probe, which we also used in this project. When inserted into the soil, via an access tube, the neutron probe emits fast neutrons which are moderated by water molecules in the soil. The count of resultant slow neutrons reflected back to the probe is used to calculate soil water content from established calibration functions. We were concerned that the emitted fast neutrons would not distinguish between the water contained in potato tubers and that in the surrounding soil, and that the presence of tubers close to access tubes installed in the potato ridge may result in the soil water content being over-estimated. Two field experiments were conducted to test this theory and it was found that as tuber fresh weight increased up to 1400g per 30cm length of row, the over-estimation of soil water content by the neutron probe at 20cm depth approached 9mm. This is a highly significant error when considered in relation to the optimum soil moisture depletion limits of 20-25mm for varieties like Delaware and Russet Burbank on the soil types used in this project. Estimates of soil water content by neutron probe at 30cm depth were not significantly affected by the presence of potato tubers in the ridge. Therefore, these data suggest that, when using neutron probes for monitoring soil moisture levels in potato crops, readings at 20cm depth should either be corrected according to the fresh weight of tubers present, or water content at this depth should be monitored by some other means (eg. gravimetrically).

Note: A summary of each chapter of this report is included at the start of the chapter.

2.0 PROJECT STAFF AND COLLABORATORS

Murray Hegney - Project Principal Investigator and Manager

Harold Hoffmann - Project Technical Officer

Gavin D'Adhemar - Technical Officer, Manjimup Horticultural Research Centre

Staff of Manjimup Horticultural Research Centre

3.0 PUBLICATIONS ARISING OUT OF THIS WORK

Seminar/Conference Proceedings

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4.0 SURVEYS OF POTATO GROWER IRRIGATION PRACTICES AND IRRIGATION SYSTEM OPERATION IN THE MANJIMUP-PEMBERTON AREA

M.A. Hegney

Summary

Until 1989, no objective data had been collected on the irrigation practices of potato growers in the Manjimup-Pemberton area of Western Australia. It was generally believed that most growers were over-irrigating and were not responding adequately to changes in crop water demand during the growing season.

In addition to a lack of information on irrigation scheduling practices, little was known about the relative operating efficiencies of irrigation systems commonly used in the area. Irrigation systems which uniformly deliver water are just as important as maintaining the correct irrigation schedule.

The objectives of the two brief surveys reported here, conducted between 1989 and 1991, were to estimate the extent of over and under watering within commercial potato crops grown in the Manjimup-Pemberton area; to collect preliminary data on the soil moisture deficits at which commonly grown potato varieties begin to experience moisture stress; to identify how the most common irrigation systems used by growers in the area were operated and any problems with system set-up and operation that should be corrected.

Major results

- The survey of irrigation practices provided anecdotal evidence that different potato varieties have different soil moisture depletion limits. The following soil moisture depletion limits were indicated for crops grown on sandy loam soils - Delaware 15-20mm, Russet Burbank 20-25mm, Kennebec 25-30mm.
- The mostly fixed irrigation schedules used by potato growers in the Manjimup-Pemberton area were inadequate to meet the changing water requirements of their crops during the entire growth period. Both over and under watering events were recorded. Under watering was particularly common in the period between 60 and 100 days after planting. Over irrigation occurred at various times during crop growth. Over the entire crop growth period, average percent excess water applied to the crops surveyed in 1989/90 was 6.13%. The use of objective irrigation scheduling techniques based on measurements of soil moisture levels in relation to appropriate critical limits could be used to help overcome these problems.
- In 1991, the most common irrigation system used by potato growers in the Manjimup-Pemberton area was a semi-permanent sprinkler system with Pope Premier® impact sprinklers on a 14 x 9m spacing with a single 3/16" jet operated at pressures ranging between 25 and 50 psi.
- Sprinkler systems of all types were commonly operated at pressures below those considered necessary to achieve acceptable application uniformities.
- A common reason for low sprinkler operating pressure was having too many sprinklers along a single lateral line, particularly where lateral lines were running up a slope. The problem could be rectified by calculating pressure loss in lateral lines

and then determining the optimum number of sprinklers per lateral to ensure the all sprinklers will operate at an acceptable pressure. Obviously, these simple calculations should be done before installing semi-permanent sprinkler systems in each new paddock.

- In 1991, the average pumping cost for irrigating potato crops in the Manjimup-Pemberton area was estimated at $708/ha/crop.

Recommendations

(a) *Extension/adoption by industry*

Results from these surveys were presented at the 6th National Potato Research Workshop, Healesville Victoria, February 1991, and at a seminar for potato growers in the Manjimup-Pemberton area in June 1992. Detailed reports were provided to all growers who participated in the surveys.

(b) *Directions for future research*

The survey of grower irrigation practices suggested that further detailed investigation was required to establish the soil moisture depletion limits which correspond with optimum yield and quality for the major potato varieties grown in the Manjimup-Pemberton area. This is, in part, addressed by the following reported work in this project.

To aid growers in the correct set-up of irrigation systems, tables or charts detailing pressure loss or recommended sprinkler number along lateral lines need to be published for all commonly used sprinkler types and arrangements.

(c) Financial/commercial benefits

Failure to respond to changes in crop water requirement during growth can result in lost income through reduced yield or tuber quality, or excessive water application levels and hence pumping costs. Variation in water application levels within a sprinkler pattern caused by poor system operating efficiency can cause significant yield variation within a potato crop, make accurate irrigation scheduling very difficult, and reduce grower returns. These surveys have identified a number of simple steps growers can take to help minimise these problems.

4.1 SURVEY OF POTATO GROWER IRRIGATION PRACTICES IN THE MANJIMUP - PEMBERTON AREA

Introduction

Until 1989, very little was known about the irrigation practices of potato growers in Western Australia. There was no widespread use of objective irrigation scheduling techniques and it was generally believed that most growers were over-irrigating and were not timing irrigations correctly in relation to crop growth stages and water demand. Equally, there was no local data on potato crop water use or the optimal irrigation frequencies for different potato varieties.

Aims

(1) To collect preliminary data on the soil water deficits at which potatoes, grown on the sandy loam soils of the Manjimup-Pemberton area, begin to experience stress and hence should be watered.

(2) To estimate the frequency of over and under watering in commercial potato crops grown in the Manjimup-Pemberton area during the spring-summer period.

Materials and Methods

Soil water monitoring

During the 1989/90 growing season, eight commercial potato crops were monitored. A further five crops were monitored during the 1990/91 season. In each crop, immediately after emergence, when individual plants could be identified, three aluminium neutron probe access tubes (1.0 m long) were installed in a representative area of the crop. The soil moisture content of the top 75 cm of the profile was measured twice weekly throughout the life of each crop by integrating soil moisture measurements taken at depths of 20, 30, 45, 60 and 75 cm below the top of the potato ridge. The neutron probe used was a Model 503DR Hydroprobe from Campbell Pacific Nuclear, Pacheco, California, USA. The neutron probe was not separately calibrated for each site. Rather the calibration equations supplied by the manufacturer were used.

At each site, field capacity was estimated from soil moisture measurements taken 24 hours after significant rainfall or irrigation events early in the life of the crop.

At three additional sites during the 1989/90 season, one each for the varieties Delaware, Kennebec and Russet Burbank, daily soil moisture readings were taken immediately after one or more irrigation events during the early to mid tuber bulking growth stage. At each of these sites, three replicate neutron probe access tubes were installed in a small, representative area of crop. Then, immediately following an irrigation event considered sufficient to fill the soil profile to field capacity, the sprinklers surrounding this small site were blocked off for a 10 to 15 day period (drying cycle). Daily measurements of soil moisture content during these drying cycles then enabled crop water use to be closely monitored. When a clear change (i.e decrease) in the rate of water use occurred, the soil moisture content at that time was set as the refill point. The difference between field capacity and the refill point was then set as the soil water depletion limit for that variety at that site. The soil moisture depletion limits established in this way were then arbitrarily used at other sites with the same variety to determine the number of times that the soil moisture content fell below the refill point, and hence when the crop was likely to have been under stress.

Tuber samples

In addition to the soil moisture monitoring, tuber growth was monitored in five commercial crops of Russet Burbank potatoes planted during November 1989. All tubers (i.e. >10 mm diameter) were periodically sampled from a 1 m section of row. Average tuber fresh weight was recorded and related to the number of days after planting.

Results and Discussion

Refill point estimations

Figures 1, 2 and 3 show the changes in soil moisture content during a representative drying cycle at the early to mid tuber growth stage in crops of Delaware, Kennebec and Russet Burbank, respectively. The data suggest that the soil moisture depletion level above which Delaware potatoes begin to experience moisture stress (15-20 mm) may be lower than for Russet Burbank (20-25 mm). Compared to both Delaware and Russet Burbank, these data suggest that Kennebec may be able to tolerate a higher soil moisture depletion level (25-30 mm). Given that the data for each variety was taken from a different site, it is difficult to confidently say that these apparent differences in tolerable soil moisture depletion levels are real. Replicated soil moisture deficit experiments, or data from surveys of a larger number of field sites, is required to establish the optimal soil moisture depletion limits for each variety. Nonetheless, for the purpose of determining the degree of over- or under-watering on individual sites in this survey, the soil moisture depletion limits established here were applied to other surveyed sites according to the variety used.

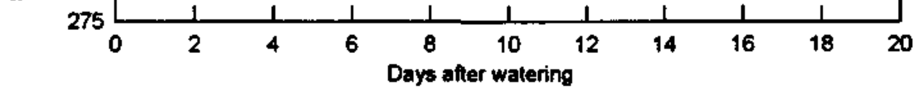

Figure 1. Changes in soil moisture content with time during two drying cycles in a crop of Delaware potatoes growing on a loamy soil in the Manjimup - Pemberton region of WA at the mid tuber growth stage. Data points are means of three replicate readings.

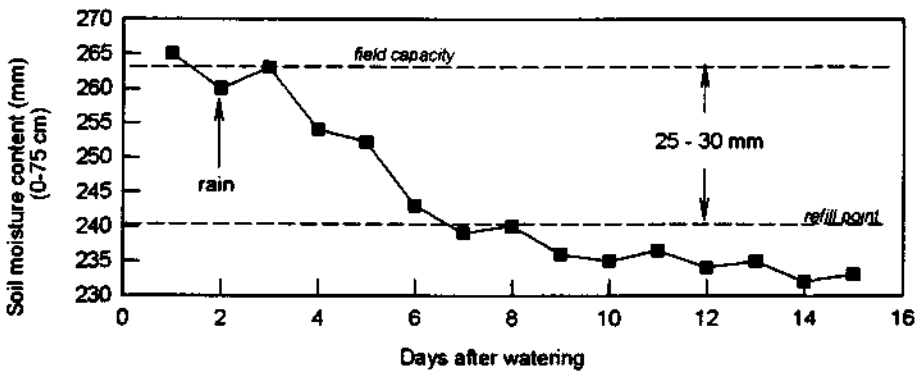

Figure 2. Changes in soil moisture content with time during two drying cycles in a crop of Kennebec potatoes growing on a loamy soil in the Manjimup - Pemberton region of WA at the mid tuber growth stage. Data points are means of three replicate readings.

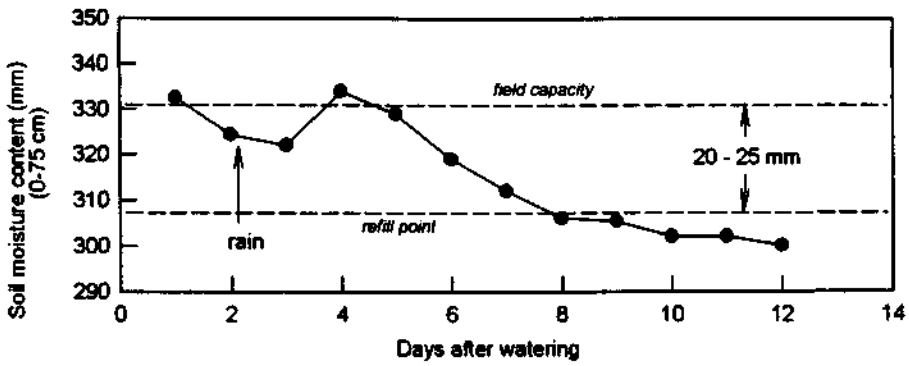

Figure 3. Changes in soil moisture content with time during two drying cycles in a crop of Russet Burbank potatoes growing on a loamy soil in the Manjimup - Pemberton region of WA at the mid tuber growth stage. Data points are means of three replicate readings.

Tuber growth in Russet Burbank potatoes

As shown in Figure 4, in Russet Burbank potatoes, tuber growth begins around 40 days after planting. The most rapid tuber growth occurs between 60 and 100 days after planting. The period of rapid tuber growth typically coincides with the period of maximum crop water use. Maintaining adequate soil moisture levels during this period is critical to achieving maximum potential yield.

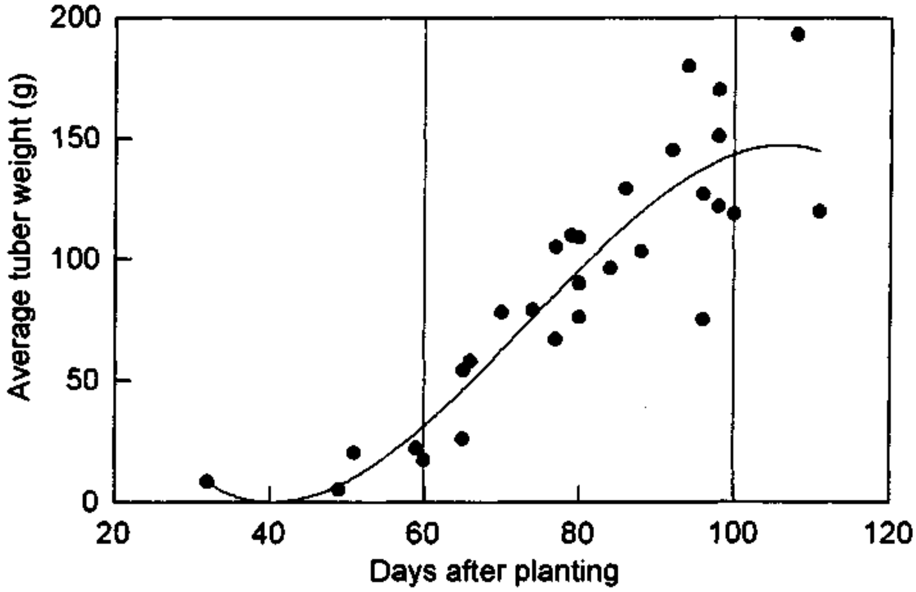

Figure 4. **Relationship between time after planting and average tuber weight for Russet Burbank potatoes. Data are from periodical one metre row samples from commercial crops during 1990/91. The equation of the fitted line is**

$$235.7-13.35x+0.23x^2-1.036x^3, \quad R^2=0.807$$

Over or under watering

For crops monitored during 1989/90, over-watering was more common during the second half of the crop growth period (>60 days after planting) than in the first (Table 1). In contrast, under-watering was more common during the first 60 days after planting. Below average rainfall was recorded during the spring of 1989 when the surveyed crops were planted and so soils were drier than normal at planting. In five of the eight crops surveyed, insufficient water was applied during the first 4 to 5 irrigation events to bring the soil moisture content up to field capacity. The result was that, in these five crops, field capacity was not reached until at or just after tuber initiation.

The average percent excess water applied to the crops surveyed during 1989/90 was 6.13% (data not shown). This compares with 32% average over-watering recorded by Marshall and Gowers (1987) in potato crops in Ballarat, Victoria. It would appear that growers in the Manjimup-Pemberton area have more of a problem with under- rather than with over-watering.

In the five crops monitored during 1990/91, both the number of over- and under-watering events were highest between 60 and 100 days after planting (Table 2). This suggests that growers found it difficult to maintain a relatively uniform soil moisture regime during this important crop growth period. The average number of times that soil moisture levels fell below the refill point was particularly high at 6.2. This reflects the fact that across all sites, despite a number of over-watering events being recorded, average soil moisture levels declined during this period and were frequently not recovered until after 100 days after planting. Part of the reason for this problem is that the growers typically used fixed irrigation cycles (i.e. irrigation every 4-6 days) and applied similar amounts of water at each irrigation event (15-30 mm). There was insufficient manipulation of irrigation frequency and amount to account for changes in crop water use rates during the season.

Table 1. The number of times soil moisture content rose above field capacity (over-watering) and fell below the refill point (under-watering) during the growth of eight potato crops in the Manjimup-Pemberton area in 1989/90. (DAP = days after planting)

Site	No. times > field capacity		No. times < refill point	
Number	0-60 DAP	>60 DAP	0-60 DAP	>60 DAP
1	2	5	4	0
2	0	4	6	1
3	2	2	6	6
4	2	3	5	7
5	1	4	6	4
6	2	4	3	2
7	1	0	1	1
8	0	1	1	0
Average	1.25	2.88	4	2.62

Table 2. The number of times soil moisture content rose above field capacity (over-watering) and fell below the refill point (under-watering) during the growth of five potato crops in the Manjimup-Pemberton area in 1990/91. (DAP = days after planting)

Site	No. times > field capacity			No. times < refill point		
Number	0-60 DAP	60-100 DAP	>100 DAP	0-60 DAP	60-100 DAP	>100 DAP
1	0	5	2	9	3	0
2	0	3	3	1	9	7
3	1	2	0	5	9	3
4	2	2	3	0	8	5
5	2	3	2	4	2	1
Average	1	3	2	3.8	6.2	3.2

Depth of water extraction

The dominant soils on which potatoes are grown in the Manjimup-Pemberton area are duplex in nature. Top soils consist of gravelly loams, loams, sandy loams and loamy sands, while the subsoil is generally a mottled sandy clay or clay. Depth to subsoil varies between 40 and 100 cm, though most commonly is encountered at c. 60 cm. In all of the crops surveyed, only minimal water extraction occurred below the depth at which the soil textured changed. Where over-watering occurred, water was observed to move into the subsoil. The greatest depth of measured water extraction by potatoes was 80 cm in crop 7 (1989/90) which was grown on a loamy sand soil with a top soil depth of 100 cm.

References

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4.2 SURVEY OF POTATO CROP IRRIGATION SYSTEMS IN THE MANJIMUP-PEMBERTON AREA

Introduction
Irrigation systems which deliver water uniformly and at a known application rate are critical to the success of any irrigation scheduling program. Potato growers in the Manjimup-Pemberton area use a variety of irrigation systems with many different system configurations. While this project was aimed primarily at developing irrigation scheduling guidelines, a knowledge of existing irrigation systems and their operation was also considered important. This knowledge may enable the identification and correction of any major system problems prior to introducing irrigation scheduling. Also, factors such as correct placement of soil moisture sensors within a crop requires an ability to define areas within the sprinkler pattern which are receiving representative water application rates.

Aim
The aim of the brief survey reported here was to identify how the most common irrigation systems used by potato growers in the Manjimup-Pemberton area are operated and any problems with system set-up and operation that need to be addressed.

Materials and Methods
A written questionnaire was mailed to 72 potato growers in the Manjimup-Pemberton area in August 1991. The format of the questionnaire was kept simple by combining multiple choice questions with questions requiring only a single figure answer. It was known prior to the survey that semi-permanent sprinkler irrigation systems were the most common in the area. For this reason, the survey questions related mostly to this type of system.

39 growers responded by returning the completed questionnaires. Due to time limitations, no attempt was made to re-contact growers who failed to respond. Not all of the 39 respondents provided answers for all questions on the questionnaire.

Growers were asked what type of irrigation system they used - semi-permanent sprinklers, travelling guns or lateral move. Growers with semi-permanent sprinkler systems were asked what sprinkler heads they used and the sizes of front and back sprinkler jets. These growers were also asked for details on sprinkler and lateral spacings, lateral pipe sizes, average and maximum numbers of sprinklers per lateral, average system output (mm/hr) and sprinkler operating pressures. All growers were asked what their total irrigation pump electricity/diesel cost ($/ha) was for their 1990/91 potato crop. Finally, growers were asked what total area of potatoes they cropped during the 1990/91 season. Results were tabulated to provide an indication of the frequency of various systems and their configurations.

In addition to the questionnaire, average system application rates were measured in 11 randomly selected crops during the 1990/91 season. In each of the selected systems the sprinklers were arranged in an offset pattern. Precipitation rates (mm/hr) were measured during a standard irrigation cycle (1.5 to 3 hours) using five raingauges placed within the sprinkler pattern as shown in Figure 1. These measurements were carried out at three locations within the crop. The operating pressure of sprinklers immediately adjacent to the raingauges was measured with a hand held Bourdon pressure gauge with attached pitot tube. Average system application rates were determined by calculating the mean of all 15 raingauge measurements. In addition to these measurements, the coefficient of uniformity (CU) (Christiansen, 1942) and distribution uniformity (DU) (Jensen,1981) of system configurations as close as possible to those being used by the growers were determined using the Sprinkler Testing Software (STS) from the Australian Irrigation Technology Centre.

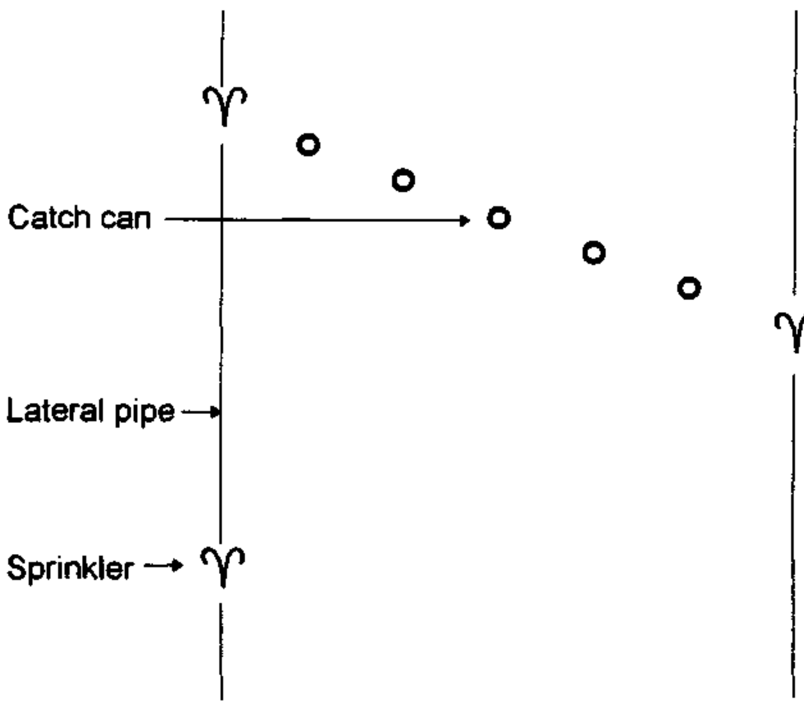

Figure 1. Arrangement of catch cans within a typical sprinkler layout.

Results

The average area of potatoes produced by the 39 questionnaire respondents during the 1990/91 season was 15ha. Cropped areas ranged between 2 and 50ha. 11 respondents produced more than 20ha and 11 produced less than 10ha.

As anticipated, most growers used semi-permanent sprinkler irrigation systems (Table 1). 11 growers used both semi-permanent sprinkler systems and travelling guns. 3 growers used both semi-permanent systems and lateral move irrigators and one grower used all three irrigation systems. All of the growers with semi-permanent sprinkler systems used 50mm (i.d.) aluminium lateral pipes and 0.75 to 1.0m x 19mm (i.d.) galvanised iron sprinkler risers.

Within semi-permanent sprinkler systems the most common sprinkler type used was the Pope Premier® impact sprinkler (Table 2). The second most common sprinkler type was the Pope Monsoon® impact sprinkler.

Table 1. Irrigation systems used by the surveyed growers (n=39).

Irrigation System	Frequency
Semi-permanent (sprinkler)	33
Travelling gun	18
Lateral move	4

Table 2. Frequency of various sprinkler types used within semi-permanent sprinkler systems.

Sprinkler type	Frequency
Pope Premier®	24
Pope Monsoon®	10
Rainspray No. 4®	6
Pope President®	1
Israle[1]	1

1. Of unknown origin

For systems using Premier® sprinklers, the most common spacing between laterals and sprinklers was 14m and 9m, respectively (Table 3). For systems using Monsoon® sprinklers, lateral x sprinkler spacing combinations varied widely from 12 x 9m to 18 x 18m (Table 4).

Table 3. Sprinkler spacings within systems using Premier® sprinklers (n=24).

Distance between laterals (m)	Distance between sprinklers (m)	Frequency
12	9	1
12	12	2
14	9	17
15	9	2
16	9	2

The average number of sprinklers per lateral in systems using Premier® sprinklers was 12 (range 5 - 22), and for systems with Monsoon® sprinklers it was 9 (range 5 - 20). The average maximum number of sprinklers per lateral was 15 (range 7 - 25) and 14 (range 7 - 26) for systems with Premier® and Monsoon® sprinklers, respectively.

Table 4. Sprinkler spacings within systems using Monsoon® sprinklers (n=10).

Distance between laterals (m)	Distance between sprinklers (m)	Frequency
12	9	1
14	14	1
15	14	2
16	14	1
16	18	2
18	14	1
18	15	1
18	18	1

All Premier® sprinklers were operated with a front jet only and the most common jet size was 3/16" (No. 12)(Table 5).

Table 5. Front jet sizes in Premier® sprinklers (n=24).

Pope Premier Jet		Frequency
Number	Size (inches)	
8	1/8	1
10	5/32	1
12	3/16	15
13	13/64	4
14	7/32	3

Within 9 of the 10 Monsoon® sprinkler systems, both front and back jets were used and the most common front and back jet combinations were 5.6 x 3.2mm and 6.8 x 3.2mm (Table 6).

Table 6. Jet combinations in Monsoon® Sprinklers (n=10).

Jet size (mm)		Frequency
Front	Back	
5.2	-	1
5.2	3.2	1
5.6	3.2	3
6.0	3.2	1
6.4	3.2	1
6.8	3.2	3

Twenty five respondents indicated they had a pressure gauge somewhere within their irrigation system. Of these, 16 were in semi-permanent sprinkler systems. All Monsoon ® sprinkler systems with pressure gauges (n=5) were said to operate at 50 pounds per square inch (psi) (sprinkler pressure). Within Premier® systems with pressure gauges (n=12), operating pressures varied between 25 and 52 psi (mean 41 psi).

The most common specified system application rate for Premier® systems was 12 mm/h (Table 7). Five of the 10 growers with Monsoon® sprinklers responded to the question on system application rate. 2 indicated an application rate of 12 mm/h. The other 3 indicated application rates of 6, 10 and 14 mm/h, respectively.

Table 7. Application rates from semi-permanent systems with Premier® sprinklers (n=17)

Application Rate (mm/hr)	Frequency
7	3
8	1
10	3
11	1
12	8
13	1

Only 8 of the 39 respondents gave in estimate of the total cost for irrigation pump electricity or diesel during the 1990/91 growing season. The estimates ranged between $285/ha and $1000/ha., with a mean of $707/ha.

The average application rates measured within 11 grower irrigation systems were very close to the application rates determined for similar system configurations using the Sprinkler Testing Software (Table 8). Application rates recorded at raingauge locations 2 and 4 (Figure 1) were generally closest to the system average application rate. The very high application rate at grower number 9 resulted in obvious surface ponding towards the end of the 1½ hour monitored irrigation cycle. As would be expected, average system application rates increased in response to increases in operating pressure and nozzle sizes and decreased sprinkler spacing. For a given nozzle size and sprinkler spacing, the coefficient of uniformity (CU) and distribution uniformity (DU) tended to increase with increased pressure. CU and DU also increased with reduced sprinkler spacings. The highest CU and DU (97.1% and 95.5%, respectively) was recorded for a system with Monsoon® sprinklers with a front and back jet combination of 6.4x3.2mm, a lateral x sprinklers spacing of 12x9m and an operating pressure of 50 psi. No STS estimates were possible for grower sites 4 and 8 because the program did not contain the sprinkler nozzle combinations or pressures that these growers used.

Discussion and Conclusions

The most common irrigation system in the Manjimup-Pemberton area was a semi-permanent sprinkler irrigation system based on 50mm aluminium lateral piping with Pope Premier® impact sprinklers on a 14 x 9m spacing with a single 3/16" jet operated at pressures ranging between 25 and 50 psi. Discussions with growers about the reasons for the popularity of this system suggest that it is simply historic. When growers have needed to update or increase the size of their irrigation systems they have approached a local irrigation equipment supplier who has supplied them with this system "off the shelf". Little or no consideration has been given to where or how the system is to be operated, or whether it is the best system for the job. A similar set of circumstances applies to the use of Monsoon® and other sprinkler types.

Table 8. Sprinkler configurations, measured application rates and STS[2] estimated application rates, coefficients of uniformity (C.U.) and distribution uniformities (D.U.) of eleven potato crop irrigation systems in the Manjimup/Pemberton area.

Grower Number	Sprinkler Type	Lateral x Sprinkler Spacing (m)	Sprinkler Operating Pressure (psi)	Nozzle Sizes	Measured Mean Application Rate (mm/h)	STS Estimates[2]			
						Sprinkler Pressure (psi)	C.U.	D.U.	Application Rate (mm/hr)
1	Premier	14 x 9	25	3/16"	7.7 (±1.0)[1]	22	76.1	62.1	7.7
2	Premier	14 x 9	35	3/16"	11.3 (±1.3)	36	81.1	70.3	10.1
3	Premier	14 x 9	50	3/16"	12.6 (±1.6)	51	84.8	78.2	12.0
4	Premier	14 x 9	50	3/16"	13.1 (±1.4)	-	-	-	-
5	Monsoon	14 x 14	30	5.2x3.2mm	6.8 (±2.0)	29	83.7	76.4	8.4
6	Monsoon	18 x 14	35	5.6x3.2mm	9.2 (±1.3)	36	80.5	69.2	9.2
7	Monsoon	16 x 14	35	5.6x3.2mm	10.6 (±1.6)	36	80.1	71.3	10.3
8	Monsoon	16 x 18	75	6.8x3.2mm	16.9 (±1.8)	-	-	-	-
9	Monsoon	12 x 9	35	6.4x3.2mm	20.4 (±1.4)	36	92.6	86.4	24.4
10	Rainspray	12 x 18	60	#15x#8	13.9 (±0.6)	58	94.2	92.0	13.7
11	President	14 x 14	35	4.9x- mm	7.5 (±0.7)	44	88.9	81.2	7.9

1. Figures in parenthesis are standard errors
2. Sprinkler Testing Software (STS) from the Australian Irrigation Technology Institute, S.A.

The coefficient of uniformity (CU) and distribution uniformity (DU) are commonly accepted measures of the application uniformity of sprinkler irrigation systems. The internationally accepted minimums for CUs and DUs are 85% and 75%, respectively (ASAE Yearbook 1979). To achieve these minimum standards using the most common Premier® sprinkler configuration, a sprinkler operating pressure of at least 51 psi would need to be maintained. Only one of the STS evaluated Premier® sprinkler systems achieved both the minimum CU and DU (Grower No. 3). The mean operating pressure specified by the survey respondents who used Premier® sprinklers was 41 psi. At this pressure the uniformity of water application from these systems would be below the accepted minimum.

Half of the surveyed growers using Premier® sprinklers indicated that the application rate from their systems was 12 mm/h. Clearly, the application rate at pressures less than 51 psi will be less than 12 mm/h and so some growers may be over-estimating the quantities of water they are applying.

Sprinkler operating pressures must be adjusted according to the system configuration. Despite all survey respondents with Monsoon® sprinklers stating that their systems were operated at 50 psi, 4 of the 5 monitored Monsoon® systems had sprinkler operating pressures of 35 psi or less. At these low pressures, CUs and DUs were generally below the accepted limits. Dependent upon nozzle sizes and sprinkler spacing, 35 psi may be sufficient pressure for some Monsoon® sprinkler systems. If the operating pressure used by grower number 5 (Table 8) was increased to 35 psi, acceptable CUs and DUs would be achieved. However, higher pressures are required for other configurations. For example, for grower number 7, an operating pressure of 60 psi would be required to achieve acceptable CUs and DUs. The application uniformities of each of these systems would also be improved by reducing the sprinkler and lateral spacings.

The application uniformity of the system used by grower number 9 (Table 8) was very high due to the close sprinkler spacing. However, the very high application rate of this system resulted in surface ponding which indicates that the infiltration rate of the soil was exceeded during the irrigation cycle. In this situation, runoff and soil erosion could become a problem. The infiltration rate of the soil is an important consideration when designing irrigation systems.

Pressure loss in lateral pipes must also be considered when designing irrigation systems. Factors such as slope of the ground and sprinkler spacing affect the number of sprinklers that can be operated efficiently along a lateral pipe. 10% variation in sprinkler operating pressure, above and below the average operating pressure, is considered satisfactory in an overhead sprinkler irrigation system (Luke, 1990). Therefore, if the average operating pressure should be 50 psi, the maximum recommended pressure loss along a lateral line in 5 psi (3.55 m of head). If Premier® sprinklers with 3/16' jets are spaced at 9 m intervals along 50 mm aluminium lateral pipe on flat ground, the maximum number of sprinklers per lateral is 10 (Figure 2). If the lateral pipe runs up a 2% slope, the optimum number of sprinklers is reduced to 8 (Figure 3). Slopes as high as 6% are common in the Manjimup/Pemberton area. Only 5 sprinklers per lateral should be used on lateral lines running up a 6% slope (Figure 4). When laterals run down a slope, the optimum number of sprinklers per lateral increases to 12 and >13 for 2% and 6% slopes, respectively (Figures 5 and 6). Similar calculations can, and should be performed for all sprinkler types and spacings prior to system installation.

The average cost per hectare of power or diesel for pumping estimated by 8 survey respondents ($708/ha) is similar to irrigation pumping costs listed in enterprise budgets for potatoes produced in the Manjimup-Pemberton area (Eckersley *et al.* 1991).

Acknowledgements
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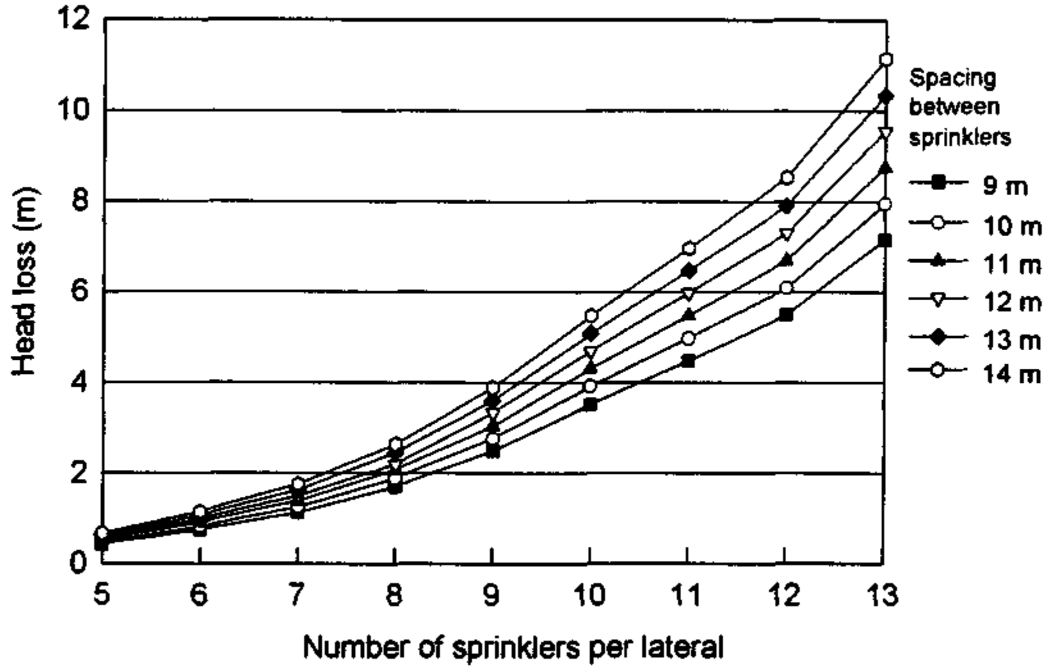

Figure 2. **Head loss in 50 mm aluminium irrigation pipe with varying numbers of Pope Premier 3/16" single jet sprinklers operating at 50 psi at six different sprinkler spacings along a lateral on a 0% slope.**

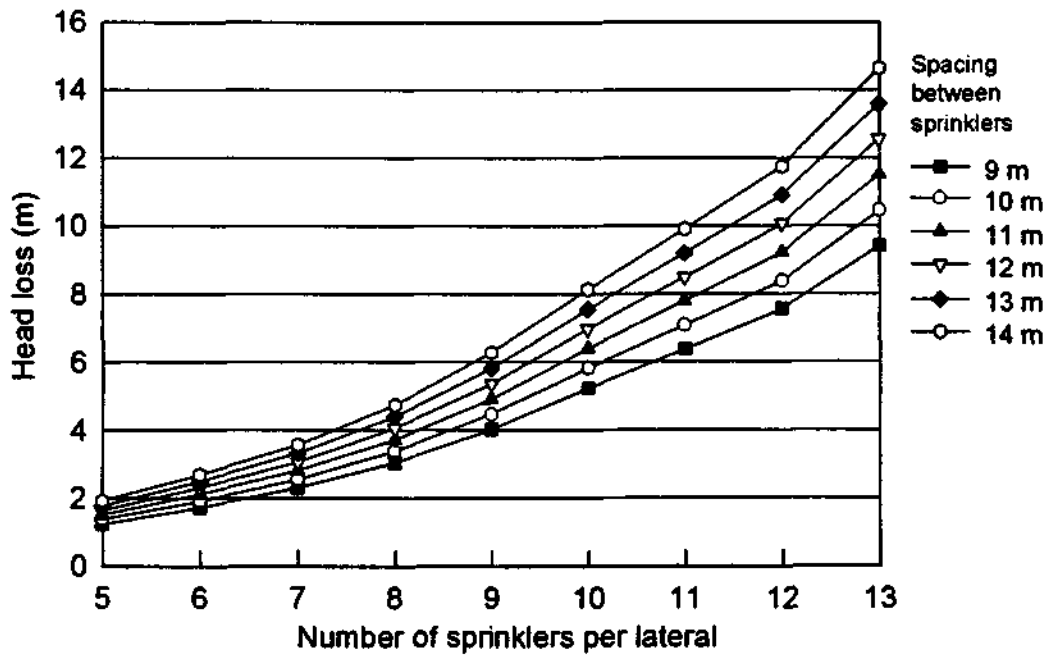

Figure 3. **Head loss in 50 mm aluminium irrigation pipe with varying numbers of Pope Premier 3/16" single jet sprinklers operating at 50 psi at six different sprinkler spacings along a lateral running up a 2% slope.**

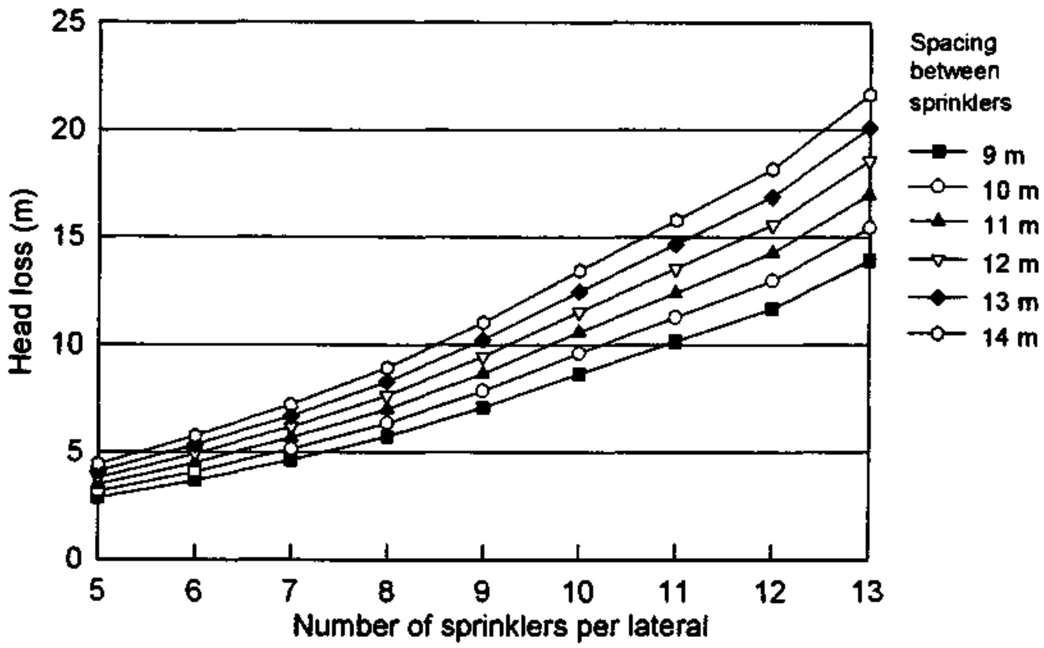

Figure 4. **Head loss in 50 mm aluminium irrigation pipe with varying numbers of Pope Premier 3/16" single jet sprinklers operating at 50 psi at six different sprinkler spacings along a lateral running up a 6% slope.**

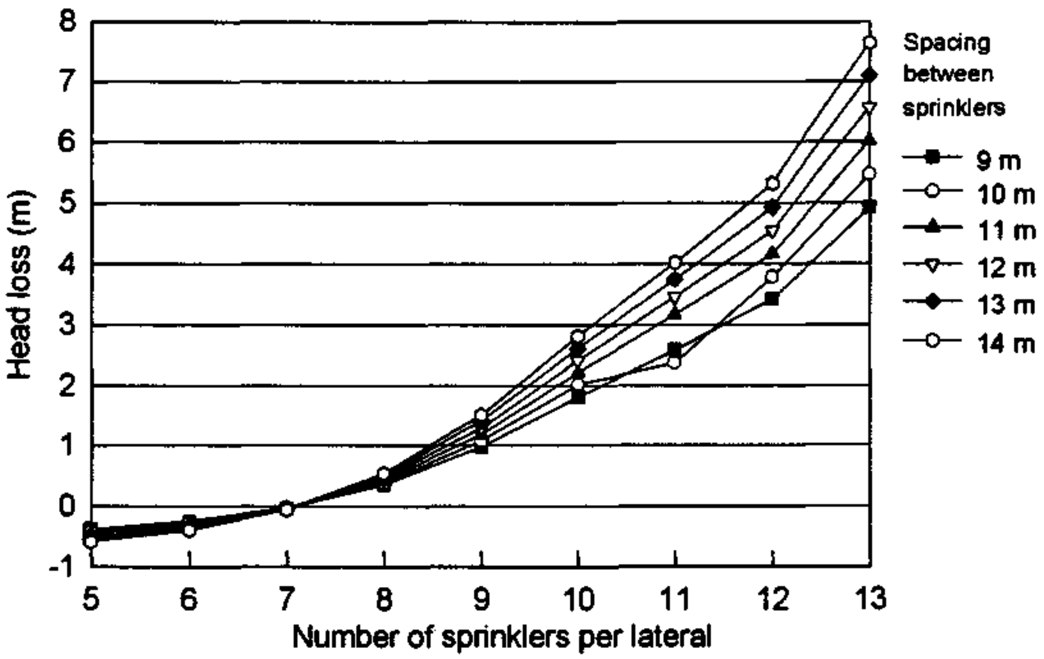

Figure 5. **Head loss in 50 mm aluminium irrigation pipe with varying numbers of Pope Premier 3/16" single jet sprinklers operating at 50 psi at six different sprinkler spacings along a lateral down a 2% slope.**

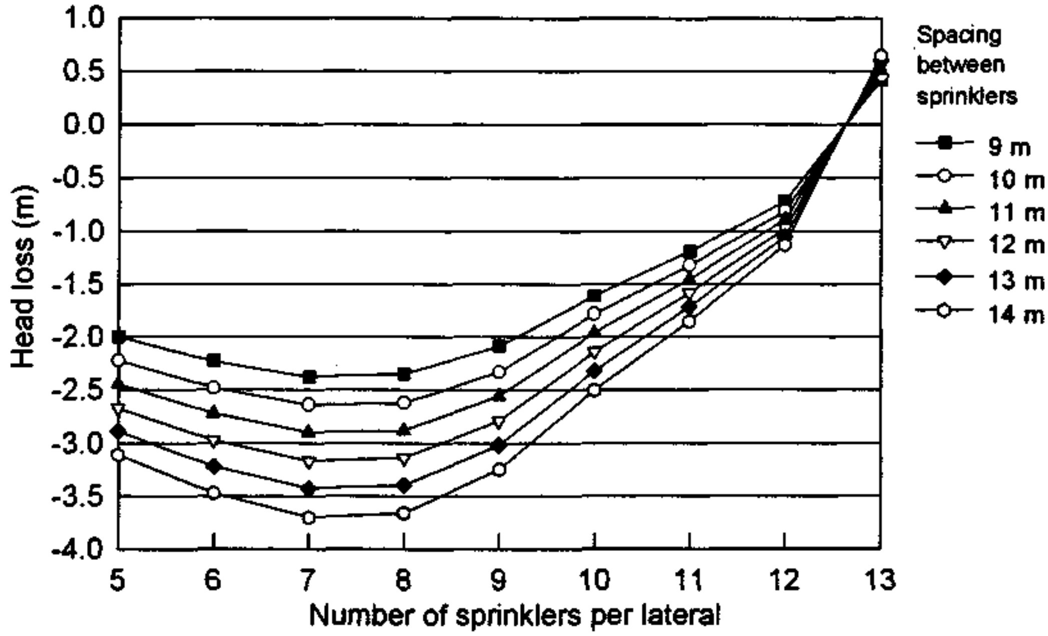

Figure 6. **Head loss in 50 mm aluminium irrigation pipe with varying numbers of Pope Premier 3/16" single jet sprinklers operating at 50 psi at six different sprinkler spacings along a lateral running down a 6% slope.**

5.0 IRRIGATION MANAGEMENT OF DELAWARE, CADIMA AND KENNEBEC POTATOES

M.A. Hegney and H.P. Hoffmann

Summary

Delaware is the most important fresh market potato variety in Western Australia, representing approximately 60% of total fresh potato production. Local experience has shown that, like many medium to long season potato varieties which produce oblong shaped tubers, Delaware is sensitive to is sensitive to water stress. Fresh potato consumers demand potatoes that have even shape and are without growth deformities, either external or internal. Therefore, to maximise returns, growers producing Delaware potatoes must manage all inputs to maximise both yield and tuber cosmetic quality. Irrigation management is critical in this regard.

Until 1992, Cadima potatoes were being used in Western Australia for both French fry and crisp manufacture out of storage. At present, only small quantities of this Western Australian bred variety are produced for crisp production. Local experience suggested that Cadima was less sensitive to water stress than Delaware and so may require a different irrigation regime.

Kennebec potatoes are commonly grown in Western Australia for use primarily in early season French fry production. Overseas experience suggests that the strong root system and relatively early maturity of this variety enable it to tolerate lower soil moisture levels compared with Delaware or Russet Burbank.

Experiments were conducted to define the soil moisture limits within which Delaware, Cadima and Kennebec potatoes should be irrigated to achieve maximum yield and tuber quality.

Major results

- When irrigation was applied in response to the same soil moisture deficit during all growth stages, total and marketable yield of Delaware was maximised by maintaining the available soil moisture level above ~77%. On a sandy loam soil type, this available soil moisture level corresponded with a soil water potential (SWP), measured at 30 cm depth below the top of the ridge, of ~ -25 kPa.
- To maximise the proportion of Premium grade tubers (ie. tubers without malformations such as pointed stem ends), the available soil moisture level for Delaware potatoes should be maintained above 80% (SWP -20 to -25 kPa) during the period between emergence and early tuber growth. Subsequently, during the main tuber bulking period and crop senescence, the data presented here suggests that available soil moisture levels can be allowed to drop to as low as 65% (SWP -60 kPa) between irrigations without having a significant affect on yield or tuber quality. However, if the soil is permitted to dry to such levels, large amounts of water (50-55mm) need to be applied to return the soil profile to field capacity. Such large amounts of water applied in a single irrigation may lead to problems with soil erosion. Therefore, it is suggested that the available soil moisture levels should not be allowed to fall below 72 to 75% (SWP -40 to -35 kPa) when irrigating Delaware potatoes.

- Total and marketable yield of Cadima potatoes, together with tuber specific gravity, were significantly reduced when the available soil moisture level fell below 72% between all irrigation events during crop growth. On the soil types studied, this available soil moisture level corresponded with a soil water potential, measured at 30cm depth, of ~ -40kPa.
- No differences in the total and marketable yield were recorded when Kennebec potatoes were irrigated at soil water potentials, measured at 30 cm depth, ranging between -15 kPa and -40kPa. This suggests that there is no benefit in irrigating Kennebec crops at soil water potentials above -35 to -40 kPa.

Recommendations

(a) *Extension/adoption by industry*

The results from these field experiments were presented to Western Australian potato growers at seminars in September 1990, August 1991, June 1992 and September 1996. Several publications were also produced. These included two articles in the "Potato Grower" magazine, and a Farmnote (No. 107/91, Agdex 262/561) on the use of tensiometers for scheduling irrigation in potato crops

(b) *Directions for future research*

The results presented here provide a good foundation on which to base irrigation scheduling in Delaware potato crops grown on sandy loam soils in the Manjimup-Pemberton area of Western Australia. However, Delaware potatoes are grown on many other soil types (from deep sands to loams) in Western Australia and further work is required to develop irrigation scheduling guidelines for this variety on these other soil types and to examine the interaction between irrigation and nutrition management, particularly on sandy textured soils.

This work provides only a preliminary indication of the relative irrigation requirements of Cadima and Kennebec potatoes. More work is required for further refine a set of irrigation management guidelines for these varieties.

(c) *Financial/commercial benefits*

Improvement in yield and quality which can be made with the use of correct irrigation management practices contribute directly to industry efficiency and profitability. In the case of fresh market potatoes (eg. Delaware), increasing the proportion of Premium grade tubers significantly increases grower returns, while also having a positive impact on total potato sales. Similarly, the correct irrigation management is essential to the production of tubers free of internal quality problems and of the desired size.

5.1 EFFECT OF SOIL MOISTURE DEPLETION LEVELS ON YIELD AND QUALITY OF DELAWARE AND CADIMA POTATOES *(Experiment 89MC18)*

Introduction
Delaware and Cadima are two important potatoes varieties for the Western Australian potato industry. In 1989/90, 85% of the fresh market potatoes grown in Western Australia were Delaware. In the same year, Cadima represented 35% of the processing potatoes produced in this State.

With the advent of quality marketing for fresh potatoes and the stringent quality requirements of potato processors, growers are now finding it more difficult to achieve consistently high returns for their potatoes. Tuber quality is now just as important as total yield. For this reason, growers have been forced to examine their production methods for areas where improvement can be made which will result in increased production of high quality potatoes. Irrigation is one area that has been identified as having considerable scope for improvement.

Potatoes are commonly accepted as being shallow rooted and more sensitive to moisture stress than many other crops (Singh, 1969; Epstein and Grant, 1973). Also, some potato cultivars are more sensitive to moisture stress than others (Miller and Martin, 1987). There is general agreement in the literature that for maximum yields of high quality tubers, available soil moisture levels in the crop root zone should never fall below 50%, and preferably should be kept above 50% (Wright and Stark, 1990). No studies have been published on the optimum soil moisture levels that should be maintained to ensure maximum yield and quality of Delaware and Cadima potatoes.

Aim
The primary objective of this experiment was to determine the optimum allowable soil moisture depletion level to ensure maximum yield and quality of Delaware and Cadima potatoes grown in south Western Australia.

Materials and Methods
Site details
The experiment was located at the Manjimup Horticultural Research Centre (34° 18'S, 116° 7'E) on a loamy sand over mottled clay at 70-80cm (Dy5.31, Northcote, 1974) Some of the relevant soil physical characteristics are given in Table 1.

Experimental design and treatments
The experiment consisted of a factorial complete block arrangement of 12 treatments - 2 varieties and 6 irrigation treatments. The irrigation treatments were six soil moisture depletion (SMD) levels - 15, 20, 25, 35, 45 and 55mm below field capacity. Given that the available soil moisture in the top 80cm of the profile is 89mm, these SMD levels corresponded with available soil moisture levels of 83, 77, 72, 61, 49 and 38%, respectively. SMD was measured daily in each plot using a neutron scattering probe (NP) calibrated on site. The SMD in the top 80cm of the profile was measured by integrating soil moisture measurements at depths of 20, 30, 45, 60 and 75cm. When the average SMD within a treatment reached the required level, that amount of water was applied to return the top 80cm of the profile to field capacity. Water was applied to

individual plots using plot irrigators, similar to those described by Riley and Wolfe (1958). Water quality was good (EC < 100mS/m).

The treatments were arranged in four replications. Each plot consisted of 6 x 5.5m long rows, with a 1.0m buffer between plots. Row spacing was 0.8m.

Table 1. Soil characteristics of the experimental site. (Data are means of 10 samples at each depth).

Soil Depth (cm)	Field Capacity (% vol.)	Wilting Point (% vol.)	% Gravel	% Coarse Sand	% Fine Sand	% Silt	% Clay	pH (H_2O)
0-30	20.4	7.2	9.6	40.5	44.3	6.5	9.5	5.5
30-75	16.2	6.6	10.6	39.6	47.6	4.0	9.3	6.0
75-120	25.2	12.4	29.2	29.1	39.8	7.8	24.0	6.0

(Note: Field Capacity was measured in the field by saturating a bare soil area and then measuring soil moisture content using a neutron probe. Wilting point is the measured soil moisture content at -15 bar suction. Gravel >2.0mm, coarse sand 2.0-0.2mm, fine sand 0.2-0.02mm, silt 0.02-0.002mm, clay <0.002mm.)

Site preparation

A five year old grass-clover pasture was growing on the trial site prior to the experiment. This pasture was sprayed with glyphosate (3L/ha Roundup®) on 30 September, 1989. The area was cultivated using a mould board plough on 17 August, 1989. Fenamiphos (24L/ha Nemacur®) and chlorpyriphos (6L/ha Lorsban®), together with 265 kg/ha KCl, 50 kg/ha $MgSO_4$ and a trace element mix containing 15kg/ha $CuSO_4$, 7.5kg/ha ZnO, 10kg/ha $MnSO_4$ and 15kg/ha Borax were applied on 30 October and incorporated with a roto-tiller.

Crop management

Two days before planting, Potato manure E (3.5% N, 7% P, 6.6% K) was banded at 3.0t/ha into ridges using a mechanical planter. Certified seed tubers which had been harvested the previous autumn and stored at 4°C were removed from storage 3 weeks before planting. The seed was cut to 45-55g setts and dusted with tolclophos-methyl (2kg/t Rizolex®) before being hand planted into preformed ridges on 3 November 1989. Delaware was planted at an in row spacing of 15cm (83333 plants/ha) and Cadima at 25cm (50000 plants/ha) in accordance with district recommendations. 100% emergence was recorded in both varieties on 29 November 1989 at which time final hilling occurred.

200kg/ha urea was applied on 13 December 1989 and again on 29 December 1989. Metribuzin (500g/ha Sencor 700®) was applied on 29 November 1989 for general weed control. Methamidophos (700mL/ha Nitofol®) and permethrin (150mL/ha Ambush®) were applied at regular intervals for the control of potato tuber moth and aphids. Chlorothalonil (2L/ha Rover®) was applied weekly for control of early blight (*Alternaria solani*).

Consumptive water use
Total soil moisture (TSM) was measured immediately before and after the growing season in each plot to a depth of 120cm and consumptive water use (CWU) was estimated using the water balance method:

CWU = TSM at (11/12/89) - TSM at 90% plant senescence + applied irrigation + rainfall

Drainage below 120cm was considered negligible and was ignored.

Harvest and grading
The trial was harvested on 1 March 1990 using a single row harvester. After the removal of rejects (greens, rots, knobs) which were counted and weighed, all remaining tubers were graded into different size categories according to variety:

Delaware -	30-80g	Cadima -	0-100g
	80-150g		100-250g
	150-350g		250-450g
	350-450g		>450g
	>450g		

In accordance with W.A. Potato Marketing Authority standards, Delaware tubers were also graded into Premium, Grade 1 and Grade 2 tubers based on their cosmetic quality after washing.

Specific gravity was determined on a 3.5kg sample of 150 - 350g tubers from each plot using the weight in air - weight in water method.

Data analysis
All data were analysed by analysis of variance using the MASS V3.5 statistical package.

Results

Growth periods
Drier treatments generally remained green for longer than the wet treatments (Table 2).

Table 2. Average growth periods of the different soil moisture deficit (SMD) treatments for Delaware and Cadima.

SMD (mm)	Days from planting to 50% senescence	
	Delaware	Cadima
15	111	111
20	111	111
25	111	119
35	111	119
45	119	130
55	119	130

Water applied and irrigation frequency
For both varieties, the total amount of water applied decreased as the SMD increased (Table 3). Irrigation frequency followed a similar trend.

Before irrigation scheduling commenced, both varieties received 96.3mm of irrigation and 20mm of rain. Due to the delay in harvest time and the need to maintain the surface soil moist when irrigation scheduling ceased, both varieties received a further 49mm of irrigation and 157.7mm of rain over a period of four weeks between crop senescence and harvest.

Table 3. Effect of soil moisture deficit (SMD) treatments on total irrigation water applied, irrigation frequency, consumptive water use (CWU) and water use efficiency (WUE = kg marketable yield/mm CWU) of Delaware and Cadima potatoes.

SMD (mm)	Applied Irrigation (mm)		No. of Irrigations		CWU (mm)		WUE	
	Del	Cad	Del	Cad	Del	Cad	Del	Cad
15	402	355	23	22	478.4	447.9	110.5	104.0
20	356	337	16	15	433.6	432.1	120.7	106.7
25	384	356	14	14	472.4	453.1	96.1	99.5
35	313	301	10	9	399.0	404.7	116.2	103.5
45	230	228	6	6	336.7	336.7	136.9	110.0
55	166	224	4	5	281.0	335.5	125.2	99.0
l.s.d. ($p<0.05$)					14.1	15.5	20.7	ns

Consumptive water use
The consumptive water use data shown in Table 3 do not include water used for establishment and maintenance after plant death which can vary with different growers according to their management practices. For both varieties, there was a clear trend of increasing CWU with decreasing SMD.

Water use efficiency (WUE)
Irrigation treatments had no significant effect on the WUE (kg marketable tubers/ha/mm of CWU) of Cadima with 99 to 110kg of marketable yield produced per mm of water consumed (Table 3). For Delaware, the 20, 35, 45 and 55mm SMD treatments had the highest WUE ranging from 116 to 137kg/mm.

Soil moisture extraction patterns
Both varieties extracted most of their water requirements from the top 30cm of the profile. However, water extraction was observed down to 75cm, particularly in the drier treatments.

During the mid to late tuber bulking period for both varieties, field observations suggested that the surface soil in the more frequently irrigated treatments was becoming drier between each irrigation compared to the earlier crop growth periods. This trend was not supported by integrated measurement of the soil moisture content of the top 80cm of the profile. Examination of the soil moisture extraction data for each soil layer showed that the average soil moisture level increased during the season at the 20cm depth, remained relatively constant at 30cm and declined at 45 and 60cm (data not shown). This suggests that the average soil moisture level in the upper profile layers increased, rather than decreased, during the growing season.

For both Cadima and Delaware, the average crop factor ranged from 0.8 in the early and late crop growth periods to 1.2 during the peak growing period in the highest yielding treatments (15, 20mm deficits for Delaware and the 15, 20 and 25mm deficits in Cadima)(data not shown).

Total and marketable yields

The highest yield of both varieties was achieved with the most frequent irrigation (i.e. 15mm SMD's)(Table 4 & 5). For Delaware, both total and marketable yield was significantly ($p<0.05$) reduced when the SMD exceeded 20mm. The total yield of Cadima was significantly ($p<0.05$) reduced when SMD exceeded 35mm. However, marketable yield of Cadima was significantly reduced when the SMD between irrigations exceeded 25mm.

For Delaware, irrigation treatments had no significant effect on the number of tubers per plot. For Cadima, marketable tuber numbers were significantly ($p<0.05$) reduced when SMD exceeded 25mm (C25).

Table 4. Effect of soil moisture deficit (SMD) treatments on total and marketable yield, and total and marketable tuber numbers of Delaware potatoes.

SMD (mm)	Total Yield (t/ha)	Total No. tubers/plot	Marketable Yield (t/ha)	Marketable tubers/plot
15	59.1	555	52.9	471
20	59.8	584	52.4	485
25	52.2	539	45.3	449
35	51.2	526	46.3	453
45	51.1	506	46.0	431
55	40.4	490	35.2	406
l.s.d. ($p<0.05$)	5.3	60	6.7	57

Table 5. Effect of soil moisture deficit (SMD) treatments on total and marketable yield, and total and marketable tuber numbers of Cadima potatoes.

SMD (mm)	Total Yield (t/ha)	Total No. tubers/plot	Marketable Yield (t/ha)	Marketable tubers/plot
15	57.1	475	47.3	272
20	57.2	478	46.1	268
25	56.0	465	45.1	266
35	52.2	438	41.9	243
45	47.1	418	37.0	224
55	46.7	458	33.0	209
l.s.d. ($p<0.05$)	6.1	48	5.3	25

Tuber size grades and yield components

For both varieties, reductions in tuber yield with increasing soil moisture deficit were the result of a combination of reduced tuber numbers and reduced average tuber weight. (Table 6).

Table 6. Effect of soil moisture deficit (SMD) treatments on the average weight of all tubers and the average marketable tuber weight of Delaware and Cadima potatoes.

SMD (mm)	Average tuber weight (g)		Average marketable tuber weight (g)	
	Delaware	Cadima	Delaware	Cadima
15	119.28	129.62	125.65	186.79
20	114.35	129.38	120.23	185.69
25	108.51	130.17	112.93	183.06
35	108.40	129.01	113.71	185.79
45	112.71	120.42	118.83	176.33
55	91.81	108.97	96.61	168.42
l.s.d. ($p<0.05$)	N.S.	11.31	17.67	10.90

Increasing the SMD between irrigations above 20mm with Delaware significantly ($p<0.05$) reduced the yield of tubers in the 150-350g weight range (main marketable tuber weight range)(Table 7). For Cadima, a SMD of 55mm resulted in a significant increase in the yield of tubers in the 0-99g weight range and a decrease in the yield of tubers in the 100-450g weight range (Table 8). A SMD of 45mm decreased the yield of Cadima tubers in the 250-450g weight range.

Table 7. Effect of soil moisture deficit (SMD) treatments on the yield (t/ha) of various tuber size grades (No./plot & yield (t/ha)) of Delaware potatoes.

SMD (mm)	0-29g	30-79g	80-149g	150-349g	350-449g	450g+
15	0.48	7.1	18.8	26.0	1.0	0.4
20	0.51	8.1	18.5	24.7	1.1	0.1
25	0.42	8.0	18.3	18.3	0.7	0.4
35	0.36	8.1	18.8	18.9	0.5	0.5
45	0.34	7.5	18.2	19.8	0.6	0.1
55	0.43	8.9	16.6	9.4	0.3	0.0
l.s.d. ($p<0.05$)	ns	ns	ns	6.1	ns	ns

Table 8. Effect of soil moisture deficit (SMD) treatments on the yield (t/ha) of various tuber size grades of Cadima potatoes.

SMD (mm)	0-99g	100-249g	250-449g	450g+	Rejects*
15	9.0	32.3	13.7	1.4	3.5
20	9.5	31.9	12.7	1.6	4.2
25	8.9	33.4	10.8	0.9	4.6
35	8.7	29.2	12.1	0.6	3.3
45	9.2	28.1	7.6	0.9	2.5
55	12.2	25.7	7.2	0.0	1.2
l.s.d. ($p<0.05$)	2.1	4.3	3.1	ns	1.3

* Rejects due to deformity, greening or insect damage.

Tuber quality

Irrigating at a SMD greater than 15mm significantly ($p<0.05$) reduced the percentage of premium quality Delaware tubers (Table 9). The proportion of grade 1 tubers was reduced by the 55mm SMD treatment. The proportion of grade 2 and reject tubers was unaffected by irrigation treatments.

The specific gravity of both Delaware and Cadima potatoes increased as SMD decreased (Table 10). Significant decreases in specific gravity occurred when SMD increased above 45 and 35mm for Delaware and Cadima, respectively.

Table 9. Effect of soil moisture deficit (SMD) treatments on the percentage (on weight basis) of premium, grade 1, grade 2 and reject Delaware potatoes.

SMD (mm)	% Premium	% Grade 1	% Grade 2	% 0-29g	% Reject*
15	7.2	31.9	36.5	0.8	23.7
20	3.6	28.8	35.7	0.9	31.0
25	4.4	28.9	35.3	0.8	30.7
35	2.1	25.4	44.8	0.7	27.0
45	2.3	26.3	40.3	0.7	30.4
55	1.7	19.9	39.3	1.1	38.1
l.s.d. ($p<0.05$)	1.7	8.2	9.2	0.4	9.5

* Rejects due to deformity, insect damage, >450g.

Table 10. Effect of soil moisture deficit (SMD) treatments on the specific gravity of Delaware and Cadima potatoes.

SMD (mm)	Delaware	Cadima
15	1.0675	1.0785
20	1.0660	1.0793
25	1.0660	1.0770
35	1.0658	1.0725
45	1.0650	1.0743
55	1.0613	1.0710
l.s.d. ($p<0.05$)	0.00419	0.00361

Discussion

Total yield of Cadima remained constant at soil moisture deficits (SMD) of 15 to 35mm. However, marketable yield and tuber specific gravity were reduced by soil moisture deficits higher than 25mm. Cadima is a variety used exclusively for the production of crisps and French fries, therefore specific gravity must be considered when defining optimum production practices. For the soil type on which this work was done, our results suggest that when growing Cadima, the soil moisture deficit should not exceed 25mm. 25mm represents 30% of the available soil moisture in the top 80cm of this soil. In a review of potato irrigation research, Singh (1969) concluded that high yields could be obtained by maintaining available soil moisture above 50%. However, most of the work reviewed considered only the available moisture in the upper 30cm of the profile. Other workers (e.g. Painter and Augustine, 1976; Larsen, 1984) have since found that when the entire root zone is considered, highest yields and tuber quality will be achieved when the available soil moisture does not fall below 65% (i.e. a maximum deficit of 35%). This agrees well with the results obtained for Cadima in our experiment.

The results show that Delaware is more sensitive to moisture stress than Cadima. The total and marketable yields of Delaware were significantly reduced when the SMD between irrigations increased above 20mm. Our field observations of Delaware suggest that it is less able to regulate its rate of water use, and so maintain turgor, than Cadima. Even when the soil was close to field capacity, a hot day (ie. high vapour pressure deficit) was sufficient to cause Delaware to obviously wilt. Such stress symptoms never appeared in Cadima until the SMD increased above 35mm. Levy (1983) found that varieties with a high capacity to lower leaf osmotic potential and so maintain turgor were less susceptible to drought stress than varieties with a lower capacity to regulate leaf osmotic potential. Delaware may fall into this later category.

In both varieties, reduced yields in response to increasing SMD were associated with a shift in the distribution of tubers in the various weight categories. Increased SMD resulted in an increased proportion of small tubers and a concomitant decrease in the proportion of large and marketable size tubers. As SMD increased, a smaller fraction of lower total yields reached the sizes desirable for ware or processing potatoes. Similar effects of imposed droughts have been reported elsewhere (Steckel and Gray, 1979; MacKerron and Jefferies, 1988). The distribution of tuber sizes is important because it impacts directly on crop profitability. For example, the size range for premium grade ware potatoes is 150 to 350g. While the determination of quality grade also depends on cosmetic quality, the probability of achieving a high proportion of premium grade potatoes will increase if the proportion of tubers in this weight range increases.

The proportion of premium grade Delaware potatoes was significantly higher when the SMD was kept below 15mm compared to a SMD of 20mm. The reason for this difference is unclear, particularly considering that these treatments produced a similar proportion of tubers in the 150-350g weight range. Within other treatments, the trend for a decreased proportion of premium tubers with increased SMD was primarily due to changes in the proportion of tubers in the 150-350g weight range. The importance of high levels of premium and grade 1 tubers in determining crop profitability is illustrated in Table 11. The pricing structure of ware potatoes in Western Australia provides considerable incentive to growers to achieve high levels of premium potatoes. Maintaining low soil moisture deficits, despite the higher pumping costs to apply more water and the higher labour costs to irrigate more frequently, leads to significant profit advantages. The data presented here suggest that, on the soil type on which this work was conducted, the SMD between irrigation should not exceed 15mm when irrigating Delaware potatoes. This is equivalent to maintaining the available soil moisture level above 80%.

The reason for the increase in average soil moisture content in the 0 to 20cm soil layer during the season is unclear. One possible explanation would be interference of the neutron probe readings at this depth by water in tubers. Potato tubers can contain between 72 and 85% water. There is some disagreement in the literature on the effect of tuber growth around access tubes on the estimates of soil moisture content made with a neutron probe. MacKerron and Jefferies (1987), in a laboratory study, found no effect

Table 13. Effect of soil moisture deficit (SMD) treatments on the crop gross margin for Delaware.

SMD (mm)	Gross Margin* ($/ha)
15	4989
20	2996
25	2244
35	1887
45	1600
55	-1087

*Budget prices - Premium - $425/t
Grade 1 - $265/t
Grade 2 - $145/t

of tubers on neutron probe estimates of soil moisture content. Conversely, Foroud *et al.* (1993), in a field study, demonstrated that tuber growth around access tubes resulted in an overestimation of soil moisture content using a neutron probe. If tubers do interfere with neutron probe estimates of soil moisture content then correction factors will need to be developed to adjust neutron probe readings when tubers are present.

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5.2 EFFECT OF VARYING SOIL MOISTURE DEFICITS DURING DIFFERENT GROWTH STAGES ON THE YIELD AND QUALITY OF DELAWARE POTATOES

(Experiment 91MC21)

Introduction

In a previous experiment (89MC18) it was found that the yield and quality of Delaware potatoes was reduced when the available soil moisture level was allowed to fall below 75% between each irrigation throughout all crop growth stages. However, no attempt was made to examine the possibility that the optimal soil moisture level may vary from one growth stage to another. Wright and Stark (1990) presented data which suggested that the available soil moisture level could be decreased as rooting depth increased during potato crop growth. Such a moisture regime would reduce the total number of irrigation events required and may reduce the total water requirement.

Before making changes to the available soil moisture level during the various potato crop growth stages, it is important to appreciate the effects of moisture stress at each growth stage on tuber yield and quality. Wright and Stark (1990) stated that moisture stress during early vegetative development generally had little if any effect on tuber yield or quality. In contrast, moisture stress during the relatively short (10-14 days) tuber formation period can reduce tuber numbers and yield (Slater and Goode, 1967; Jana *et al.*, 1989), increase the incidence of malformed tubers (Nichols and Ruf, 1967; van Loon, 1981) and reduce tuber cooking quality (Stark and McCann, 1992). Moisture stress during the main tuber bulking period has a greater effect of tuber yield than quality (Millar and Martin, 1987; Martin *et al.*, 1992). Therefore, if the available soil moisture level at which irrigation events are triggered is to be reduced as crop rooting depth increases, the timing and magnitude of the reductions will need to be managed to avoid the above mentioned stress related problems.

Aim

The aim of the experiment reported here was to measure the effect of changing the available soil moisture level at which irrigation is triggered during 2 growth stages - emergence to early tuber bulking, and the main tuber bulking period - on the yield and quality of Delaware potatoes.

Materials and Methods

Site details

The experiment was located at the Manjimup Horticultural Research Centre (34° 18'S, 116° 7'E) on a loamy sand over mottled clay at 70-80 cm (Dy5.31, Northcote, 1979). Some of the relevant soil physical characteristics are shown in Experiment 89MC18 - Table 1.

Experimental design and treatments

The experiment consisted of a randomised block arrangement of 8 soil moisture deficit treatments replicated 4 times. The treatments were based on soil water potential (SWP) measured at a depth of 30 cm below the top of the potato ridge using Irrometer® tensiometers. Sufficient water was applied at each irrigation to return the soil to field capacity when the SWP reached -20, -30, -40 or -60 kPa. These SWPs corresponded with available soil moisture levels of 85, 78, 71 and 65%, respectively, based on the top 80 cm of the profile. The SWP at which irrigation events were triggered varied across 3 growth stages - emergence to tuber initiation (ie. length of largest tuber = 10 mm), tuber initiation to 50 days after tuber initiation, 50 days after tuber initiation until crop maturity (ie. 50% senescence). Hereafter, these growth stages will be referred to as 1, 2 and 3, respectively. Details of the changes in SWP between the growth stages within each treatment are given in the tables of results.

Plots of the changes in SWP during growth in each treatment are shown in Appendix 1. Because readings were taken from the tensiometers only once per day, the target SWPs for each treatments were frequently exceeded. This was particularly the case in the higher SWP treatments and resulted from a policy of not irrigating until the target SWP was reached.

Trial establishment

Prior to the experiment the site had been planted to lupins and oats. Site preparation began 10 weeks before planting when the site was cultivated using a mould-board plough. Metham sodium (500 L/ha Vapam®) was applied 8 weeks before planting and incorporated with a rotary hoe. A pre-planting fertiliser mix containing 95 kg nitrogen/ha (NH_4NO_3), 150 kg potassium/ha (KCl) and 20 kg magnesium/ha ($MgSO_4.7H_2O$) was broadcast and incorporated with tyned harrows 4 weeks before planting.

Individual plots were 5.5 m long by 6 rows wide. Row spacing was 0.8 m. Plots within each replication were separated by a 0.5 m buffer which was planted with 2 plants of the red tuber potato variety Desiree. Each replication was separated by a 2 m wide access path.

One day before planting, Potato Manure E (3.5% N, 7% P, 6.6% K) was banded at 3.5 t/ha into ridges using a mechanical planter. The experiment was planted on 5 December 1991. 50 g hand-cut seed pieces, which were dusted with tolclofos-methyl (2 kg/t Rizolex®), were planted by hand into the preformed ridges at an in-row spacing of 0.15 m (88,333 plants/ha).

Irrigation

Water was applied to individual plots using plot irrigators, similar to those described by Riley and Wolfe (1958). All plots were watered to field capacity at the first sign of emergence on 17 December 1991 and thereafter according to treatments. Water quality was good (EC <100 mS/m).

Soil moisture monitoring

In addition to the tensiometer at a depth of 30 cm, a second tensiometer was installed in each plot at 60 cm. This tensiometer provided a check on the adequacy of water applications. All tensiometer readings were taken daily between 8.00 and 10.00 am. The soil moisture profile was measured periodically throughout the experiment in one replication only using a neutron probe which had been calibrated on site. Total volumetric soil moisture (VSM) was calculated by integrating readings at depths of 20, 30, 40, 50, 60, 80, 100 and 120 cm. This data provided a second check on the adequacy of water applications. Also, total consumptive water use (CWU) was estimated for each treatment from the water balance:

CWU = VSM on 18 December 1991 - VSM at 90% plant senescence (14 April 1992) + applied irrigation + rainfall.

Drainage below 120 cm was assumed to be negligible.

Agronomic management
A total of 269 kg nitrogen/ha (Urea) was applied post-emergence as follows: 49 kg/ha on 10 January 1992, 98 kg/ha on 22 January 1992 and 3 February 1992, and 24 kg/ha on 4 March 1992. Also, 90 kg potassium/ha (K_2SO_4) was applied on 7 February 1992.

Paraquat + diquat (3 L/ha Sprayseed®) was applied at 5% emergence (19 December 1991) to control newly emerged weeds. Metribuzin (0.5 L/ha Sencor 700®) was applied when plants were approximately 15 cm high (14 January 1992) for annual weed control. Preventative control of fungal leaf diseases was achieved with weekly applications of either chlorothalonil (2 L/ha Bravo®) or iprodione (2 L/ha Rovral®) which began 2 weeks after emergence. Permethrin (150 mL/ha Ambush®) was used to control green looper and potato tuber moth and methamidophos (700 mL/ha Nitofol®) was used to control potato tuber moth and aphids when necessary. A minor infestation of wingless grasshoppers shortly after emergence was controlled with an application of maldison (500 mL/ha Malathion 500®).

Harvest and grading
All plots were allowed to naturally senescence before harvest. Three inside, undisturbed rows from each plot were harvested using a single row harvester on 28 April 1992. After washing, all tubers were counted and weighed. Any tubers with greening or rots were counted and weighed separately. The remaining tubers were graded into the following size categories - 0-50g, 50-450g, >450g. Marketable tubers were >50g and free of any defects. Marketable tubers were also graded according to whether they had growth constrictions at the basal (pointed stem-ends), centre (dumb-bells) or apical (bottlenecks) region of the tuber. The proportion (wt./wt.) of marketable tubers falling into these shape categories was recorded.

Thirty tubers (>150g) from each plot were sliced in half longitudinally and inspected for hollow heart and other internal disorders.

Statistical analyses
Data were analysed by analysis of variance using GENSTAT (GENSTAT 5 Committee 1987) and l.s.d.s ($P<0.05$) calculated for comparison of treatment means.

Results

Crop growth
There were no significant treatment effects on the period between planting and 50% senescence. This period ranged between 123 days (treatment 1) and 127 days (treatment 8). Allowing the SWP to decrease to -60 kPa between emergence and tuber initiation (treatments 4 and 8) resulted in plants showing signs of severe water stress (darkened leaves, wilted, limp plants). In contrast, when the SWP was allowed to decrease to -60 kPa between irrigations during a 50 day period after the start of tuber initiation (treatment 6), no obvious signs of plant water stress were observed.

Water applied and number of irrigation events

For treatments in which the SWP at which irrigation was triggered remained constant during all growth stages (treatments 1 to 4), the number of irrigation events and the total amount of irrigation water applied decreased as SWP decreased (Table 1). A similar trend was observed with the quantities of irrigation water applied, although in treatment 3, the quantity of water applied was similar to treatment 1. However, irrigation was applied to treatment 3 only 14 times, compared with 23 times in treatment 1.

Table 1 Irrigation water applied, number of irrigation events and consumptive water use (CWU) for each irrigation treatment.

Treat. No.	SWP regime[b]	Applied Irrigation[a] (mm)	Number of Irrigations	CWU (mm)
1	20/20/20	627	23	688
2	30/30/30	602	17	665
3	40/40/40	610	14	684
4	60/60/60	530	10	618
5	20/30/20	667	21	730
6	20/60/20	680	18	729
7	30/20/20	641	24	696
8	60/20/20	576	19	640

a. 60.8 mm of rainfall was received during the irrigation treatment period.

b. Example: 20/20/20 = irrigation applied at a SWP of -20 kPa during growth stage 1/ -20 kPa during growth stage 2/ -20 kPa during growth stage 3.

Compared with irrigating constantly at -20 kPa (treatment 1), decreasing the SWP to -30 or -60 kPa during growth stage 2 (treatments 5 and 6), resulted in a small reduction in the number of irrigation events, but an increase in the amount of irrigation water applied. In contrast, allowing the SWP to decrease to -60 kPa during growth stage 1 (treatment 8) resulted in a decreased amount of irrigation water being applied.

Consumptive water use

Treatment effects on consumptive water use were similar to those on the amount of irrigation water applied. Consumptive water use was highest in treatments 5 and 6, in which the SWP was reduced to -30 and -60 kPa, respectively, during growth stage 2. Consumptive water use was lowest in treatments 4 and 8 in which obvious visual signs of water stress were observed.

Yield

For treatments irrigated at the same SWP during all growth stages, irrigating at -20 kPa (treatment 1) produced the highest total and marketable yields (Table 2). Irrigating at -60 kPa during all growth stages (treatment 4) resulted in a significant ($p<0.05$) reduction in total yield. Marketable yield was also reduced in this treatment, but not significantly.

Allowing the SWP to decrease to -30 or -60 kPa during growth stage 2 (treatments 5 and 6, respectively) had no effect on total or marketable yields (Table 2). In fact, treatment 6 produced the highest yields of all treatments. Irrigating at -30 or -60 kPa during growth stage 1, and at -20 kPa thereafter, resulted in a reduction in both total and marketable yields, though the reductions were not significant.

Table 2 Total tuber yield, marketable tuber yield, mean tuber weight for total tuber yield and marketable tuber yield and total number of tubers per plant. Soil water potential (SWP) treatments are as described in Table 1.

Treat. No.	SWP regime	Yield (t/ha)		Mean tuber wt. (g)		Tuber no./ plant
		Total	Marketable	Total	Marketable	
1	20/20/20	72.0	57.2	186	226	4.7
2	30/30/30	68.8	57.1	195	229	4.2
3	40/40/40	65.7	55.9	192	227	4.3
4	60/60/60	58.9	49.7	165	200	4.4
5	20/30/20	69.3	58.0	180	223	4.7
6	20/60/20	76.4	65.2	199	239	4.7
7	30/20/20	63.5	50.1	165	203	4.9
8	60/20/20	66.1	52.2	187	234	4.4
l.s.d. (p<0.05)		9.6	9.5	19	19	ns

Across all treatments, where yield reductions did occur, they were due to reductions in both the average tuber weight and the number of tubers per plant, although treatment effects on tuber number per plant were not significant (Table 2). Treatments effects on tuber size are also illustrated in Table 3, where it is shown that the highest yielding treatments produced the highest yields of tubers weighing more than 150 g.

The yield of tubers rejected due to greening or rots tended to decline as irrigation frequency declined (Table 3). Despite receiving higher total amounts of irrigation water, the yield of reject tubers in treatments 5 and 6 was significantly ($p<0.05$) lower than in treatment 1.

Table 3 Yield of tubers within tuber weight ranges and the yield of tuber rejected due to greening or rots. Soil water potential (SWP) treatments are as described in Table 1.

Treat. No.	SWP regime	Yield (t/ha) within tuber weight ranges						Reject yield (t/ha)
		0-50 g	50-80 g	80-150 g	150-350 g	350-450 g	>450g	
1	20/20/20	1.8	2.2	6.8	28.4	10.3	9.5	13.1
2	30/30/30	1.5	2.1	7.5	29.2	10.9	7.3	10.4
3	40/40/40	1.5	2.0	6.2	31.1	10.2	6.4	8.4
4	60/60/60	1.8	2.1	8.4	28.0	6.8	4.4	7.5
5	20/30/20	1.9	2.3	6.9	30.6	10.0	8.3	9.4
6	20/60/20	1.6	1.8	6.5	33.2	10.7	12.9	9.5
7	30/20/20	1.8	2.3	8.6	26.6	7.9	4.7	11.6
8	60/20/20	2.1	1.6	6.7	26.7	8.5	8.6	11.8
l.s.d. (p<0.05)		ns	ns	1.4	4.1	ns	4.1	2.8

Tuber quality
No tubers were found with hollow heart. Internal brown fleck was observed in a small proportion of tubers (<5%) in all treatments, however, there were no significant treatment effects (data not shown).

The proportion of marketable tubers with pointed stem-ends increased significantly ($p<0.05$) as the SWP during growth stage 1 decreased (Table 4). Compared with irrigating constantly at -20 kPa, decreasing the SWP to -30 or -60 kPa during growth stage 2 had no effect on the proportion of tubers with pointed stem-ends. There were no significant treatment effects on the proportion of tubers with dumb-bell or bottleneck shape.

Table 4 Percentage (wt./wt. *100) of marketable tubers with pointed stem-end, dumb-bell or bottleneck shape. Soil water potential (SWP) treatments are as described in Table 1.

Treat. No.	SWP regime	Pointed stem-ends	Dumb-bells	Bottlenecks
1	20/20/20	15.8	4.1	0.5
2	30/30/30	22.3	8.6	0.3
3	40/40/40	27.1	8.0	0.2
4	60/60/60	29.0	6.0	0.1
5	20/30/20	16.0	7.0	1.2
6	20/60/20	15.1	6.2	0.5
7	30/20/20	25.3	6.7	0.1
8	60/20/20	33.9	5.6	0.0
l.s.d. ($p<0.05$)		7.0	ns	ns

Discussion
In this experiment, when irrigations were triggered at the same SWP during all growth stages, total and marketable yield tended to decrease as SWP decreased. However, a significant ($p<0.05$) reduction in yield was not recorded until the SWP decreased to -60 kPa. Given that a SWP of -60 kPa was equivalent to an available soil moisture (ASM) level of 65%, this result agrees with that obtained in experiment 89MC18 where irrigating at an ASM level of 61% resulted in a significant yield reduction.

In contrast to experiment 89MC18, where the yield of Delaware potatoes was significantly reduced when irrigation occurred at an ASM level of 72%, in the experiment reported here yields were not significantly reduced when the ASM level was allowed to fall to 71% (i.e. SWP -40 kPa) between irrigations. In experiment 89MC18, Delaware yields were not reduced when the ASM was maintained above 77%. Taking account of all of the above, it would be reasonable to suggest that, when applied across all crop growth stages, maximum yield of Delaware potatoes will be achieved by ensuring that the ASM level is maintained above 75% (SWP ~ -35 kPa).

Irrigating at a constant SWP (or ASM level) during all growth stages is not necessarily the optimum regime. Wright and Stark (1990) presented data which suggested that the total ASM within a 50 cm profile could be decreased as rooting depth increased during crop growth and treatments 5 and 6 in our experiment confirm this result. For instance, in treatment 6, after irrigating at a SWP of -20 kPa (85% ASM) between emergence and tuber initiation, allowing the SWP to fall to -60 kPa (65% ASM) between irrigations during the tuber bulking period had no effect on tuber yield. This irrigation regime did not result in a reduction in the amount of water required by the crop, in fact CWU was higher in treatments 5 and 6 than in treatment 1. However, the total number of irrigation events was reduced thus making irrigation management less labour intensive. A similar result was recorded in experiment 92MC22 for Russet Burbank potatoes.

Adopting an irrigation regime in which the SWP was allowed to decrease to -60 kPa during one or more crop growth stages may not be wise in commercial crops. When the SWP decreased to -60 kPa, between 50 and 55 mm of water was required to return the soil profile to field capacity (see SWP plots in Appendix 1). Under the conditions in which this experiment was conducted (flat site with low impact, low application rate sprinklers), it was possible to apply such large amounts of water in a single application without any water run-off. Paddocks on which potatoes are grown in the Manjimup/Pemberton region of Western Australia frequently have slopes greater than 6% and the most commonly used irrigation systems apply between 8 and 12 mm/hr. Under these conditions, applying 50-55 mm of water in a single application may result in water run-off and soil erosion problems.

Contrasting the results obtained in treatments 4 and 6 suggests that, to achieve maximum yield of Delaware potatoes, if irrigation is to be triggered at -60 kPa during the main tuber growth and crop maturation period, the SWP must be maintained above -30 kPa during the period between emergence and early tuber growth. The results obtained in treatment 8 suggest that, in terms of yield alone, irrigating at -60 kPa between emergence and early tuber growth can be tolerated, provided higher soil moisture levels are then maintained during later growth stages. Given that yields were not significantly reduced in treatment 8, compared to treatment 1, despite the plants being obviously stressed during early vegetative growth, perhaps suggests that some compensatory growth occurred in this treatment when the SWP was maintained above -20 kPa during later growth stages.

While the effect of irrigating at high SWPs in the period leading up and including early tuber growth on tuber yield may be dependent upon the SWP at which irrigations are triggered at later growth stages, the effects of high SWPs during the early growth stage on tuber shape is more consistent. Maintaining high SWP in the period before and during tuber formation is important to avoid problems with poor tuber shape, no matter at what SWP irrigation is applied during later growth stages. The percentage of tubers with pointed stem-ends increased significantly in treatments irrigated at SWPs below -30 kPa during the period between emergence and early tuber growth (treatments 3,4, 7 & 8). This same effect was observed with Russet Burbank potatoes (92MC22). Given that Delaware is sold predominantly for use as a fresh potato in Western Australia, tuber shape is an important quality criteria. Tubers with pointed stem-ends do not meet the quality specifications for premium grade potatoes according to the standards set by the WA Potato Marketing Authority. These potatoes would be down graded to class 1 or 2 potatoes, depending on the severity of the deformation. We did not rate the severity of the stem-end pointing in this experiment (only whether it was present or absent) so an accurate economic analysis is not possible. However, suffice to say that the high level of tubers with pointed stem-ends in treatments 3, 4, 7 & 8) would have resulted in reductions in the dollar return per tonne for these potatoes.

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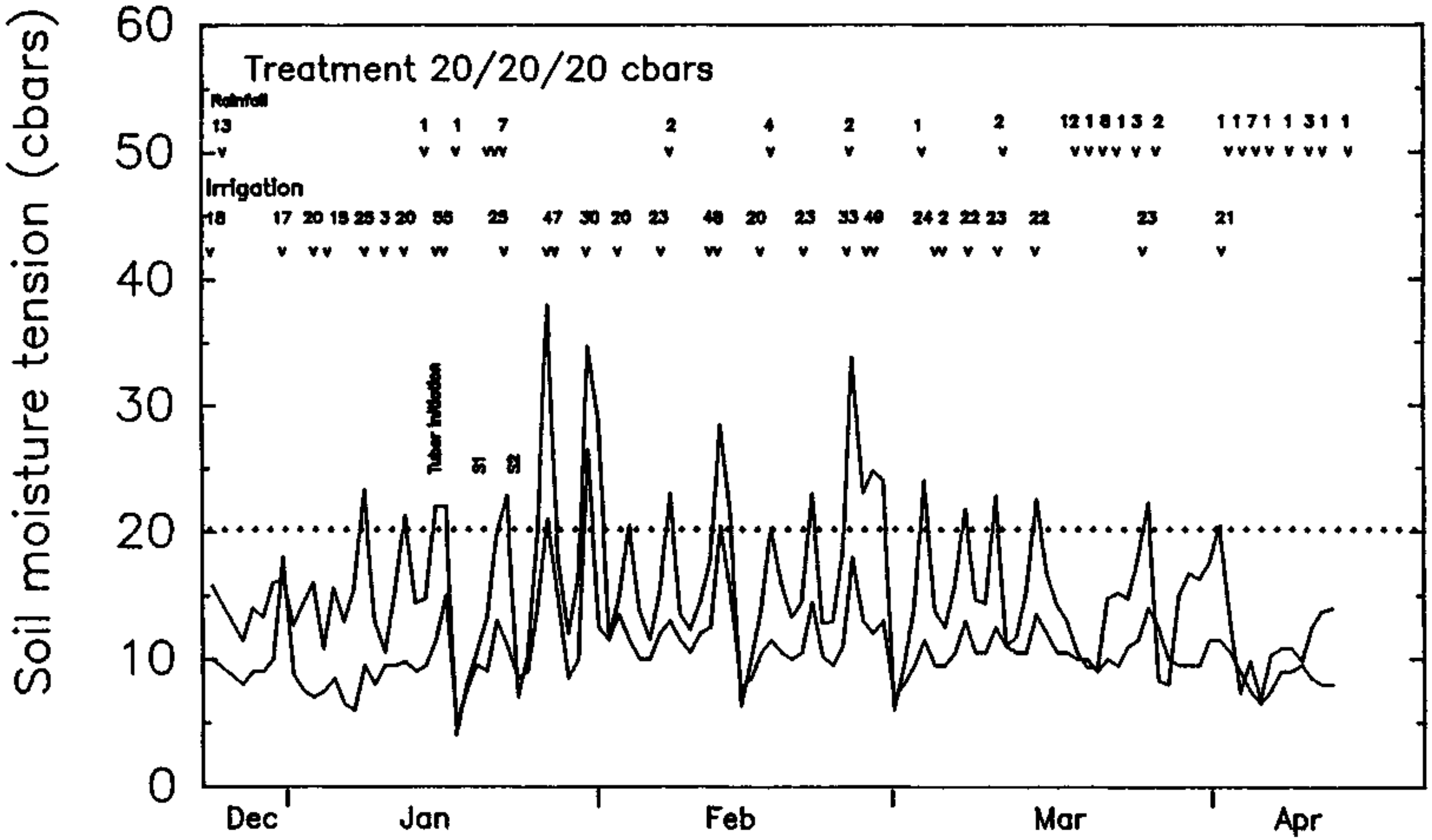
APPENDIX 1

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

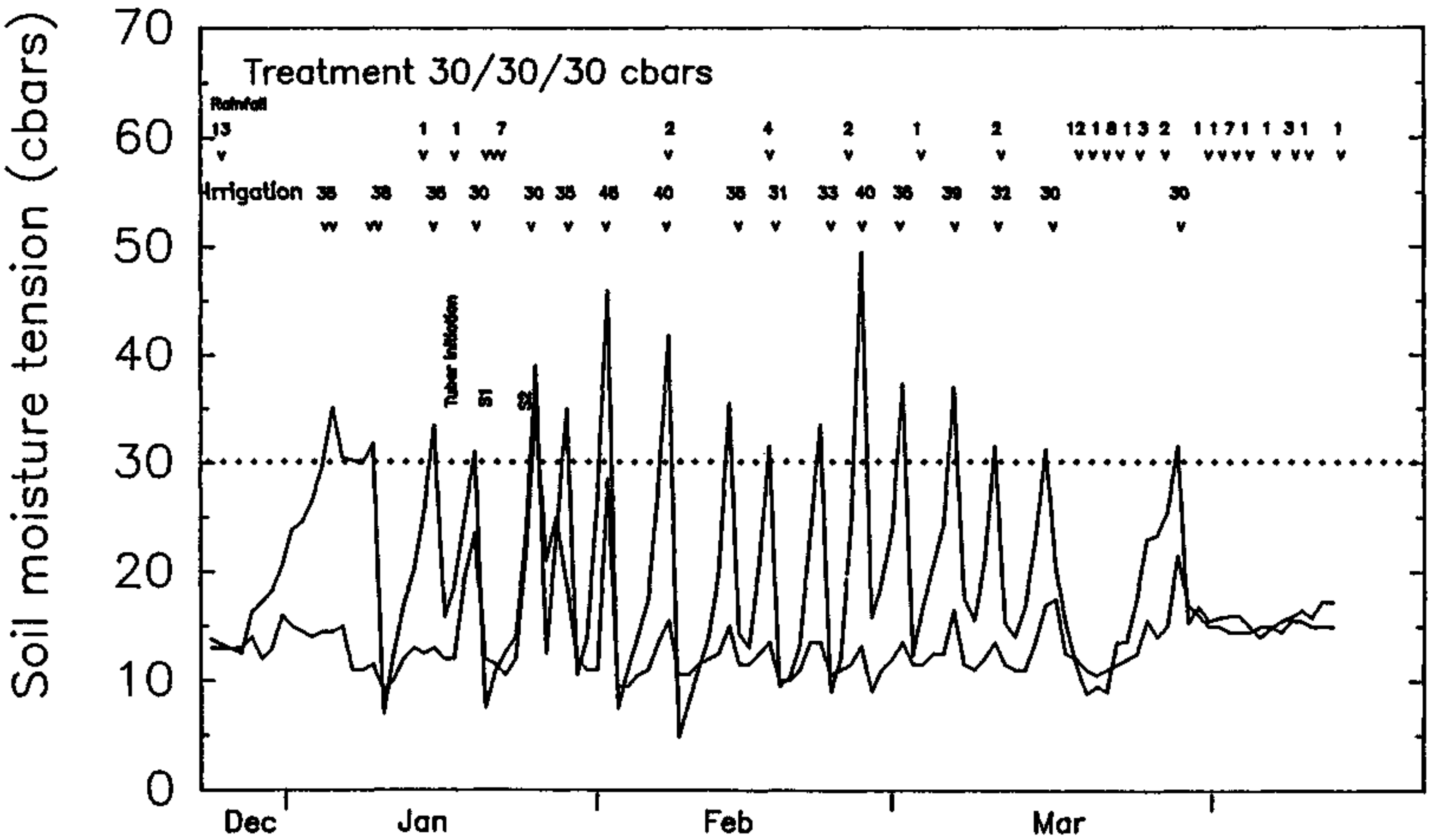
Treatment 1



APPENDIX 1 cont'

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

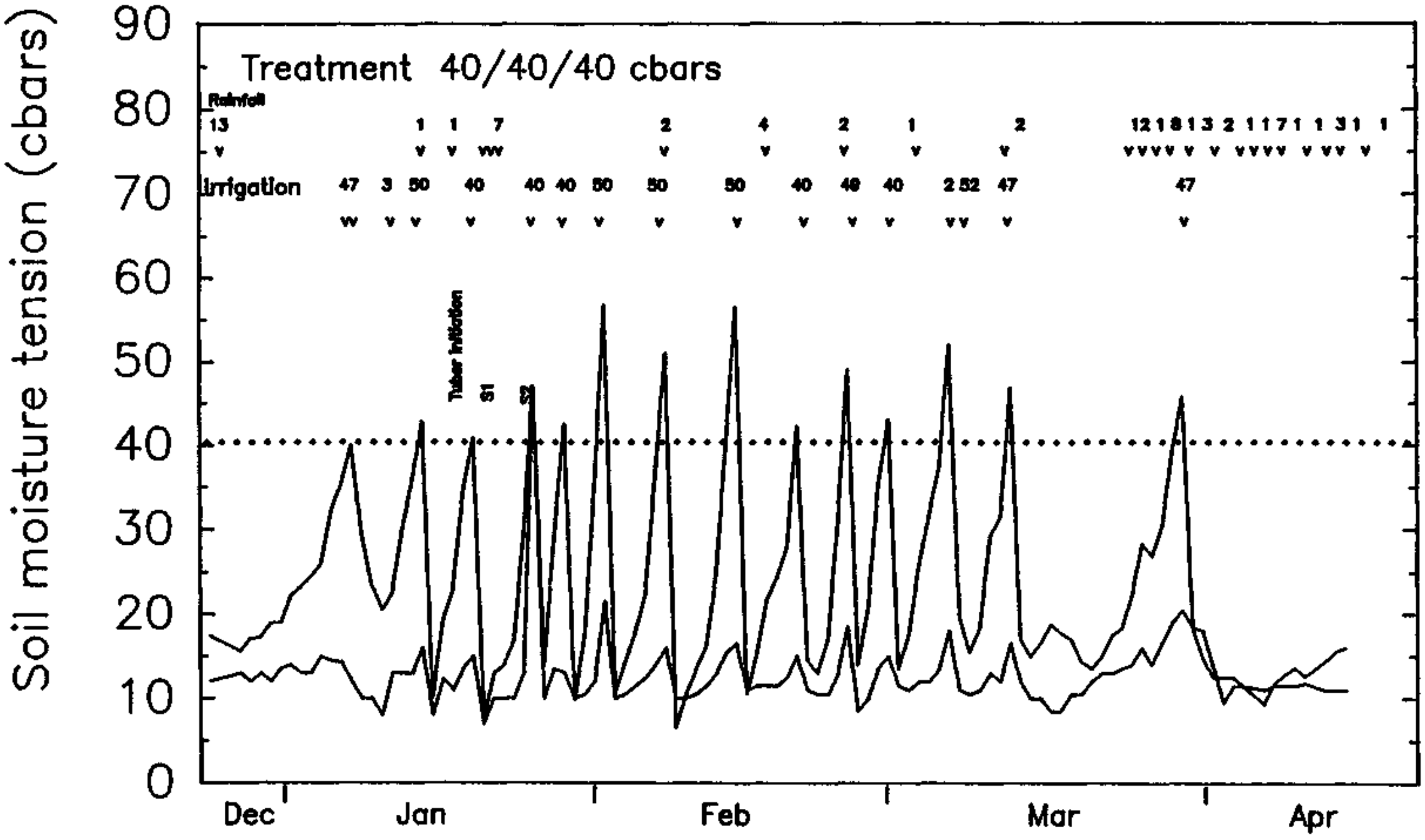
Treatment 2



APPENDIX 1 cont'

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

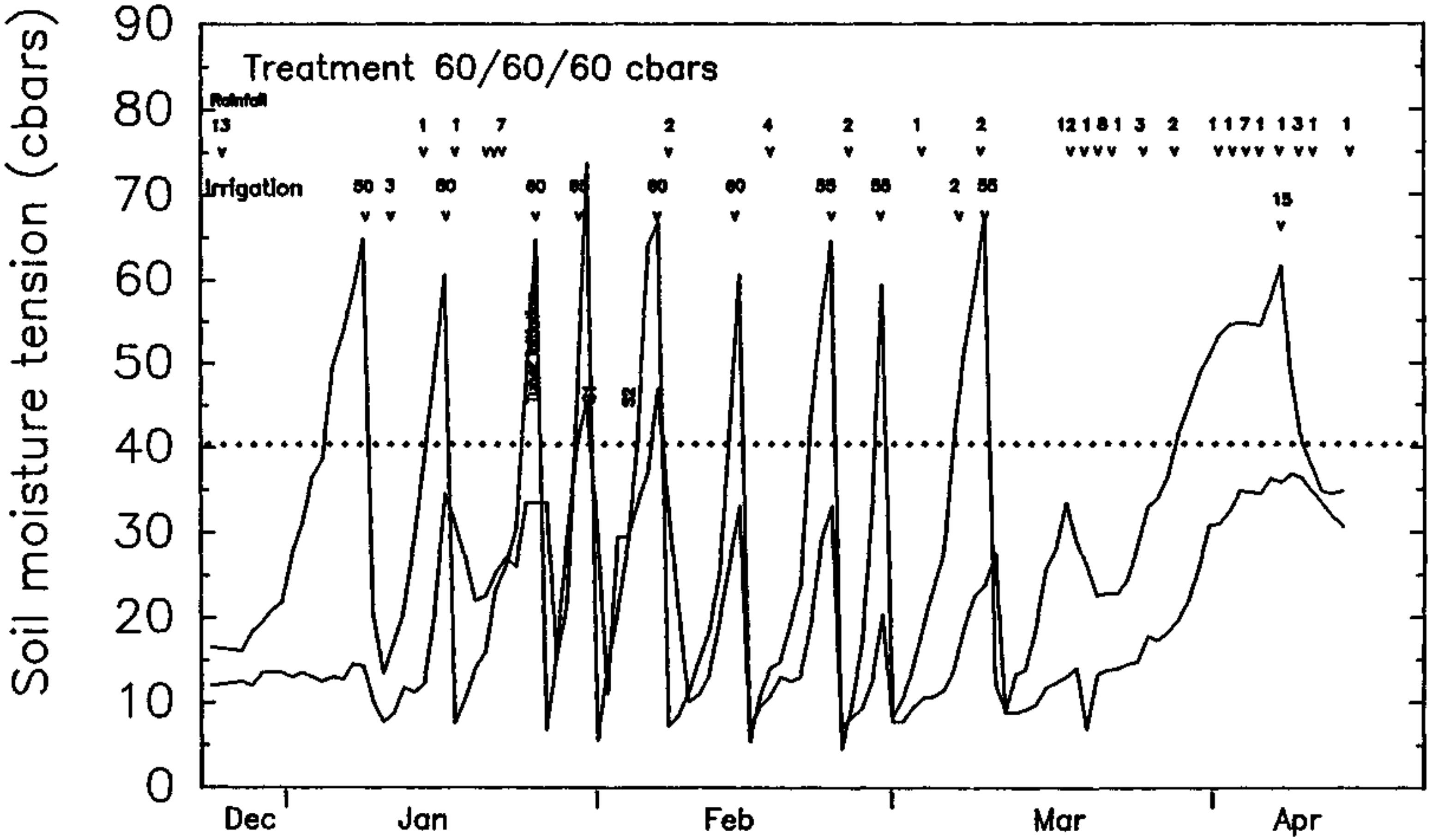
Treatment 3



APPENDIX 1 cont'

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

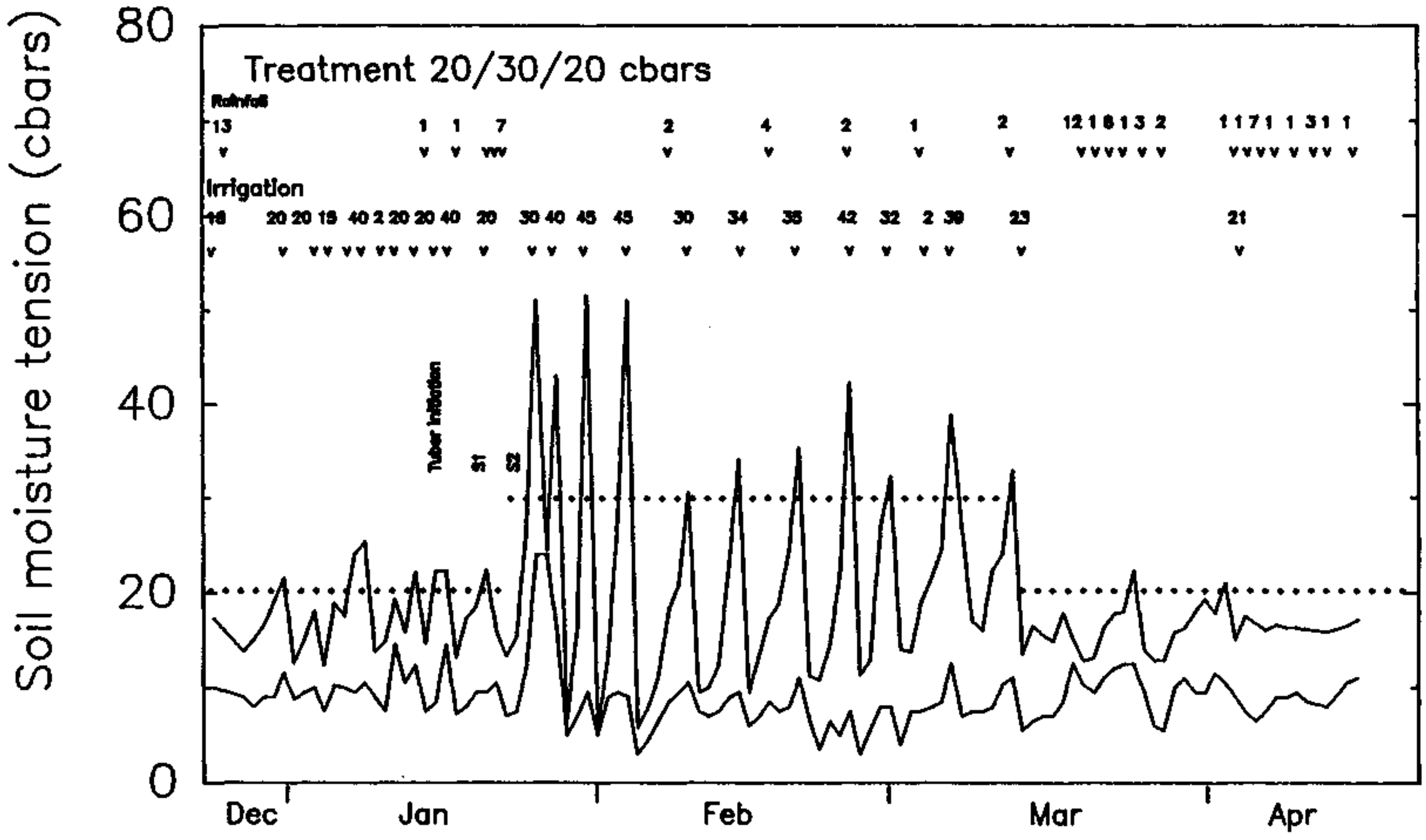
Treatment 4



APPENDIX 1 cont'

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

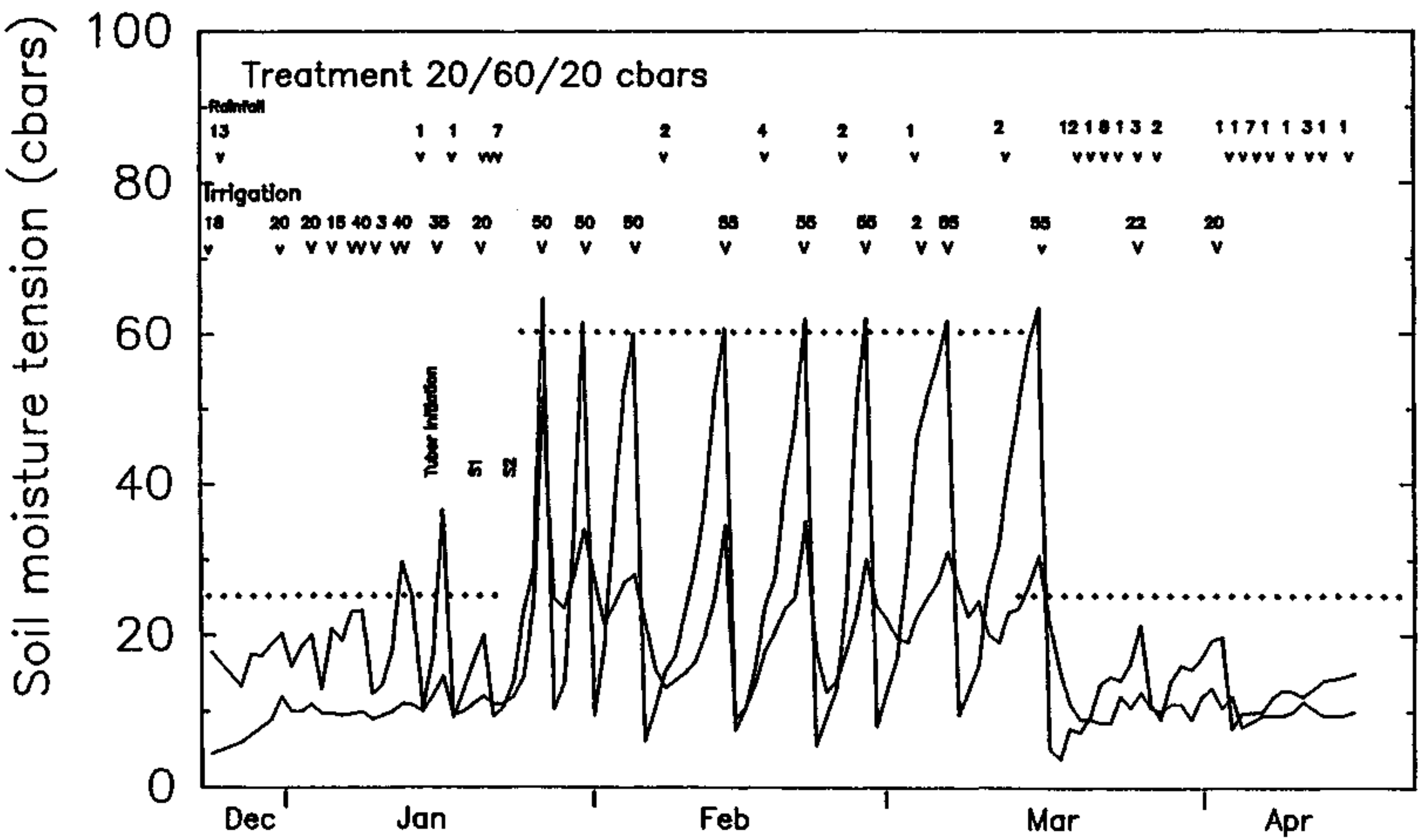
Treatment 5



APPENDIX 1 cont'

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

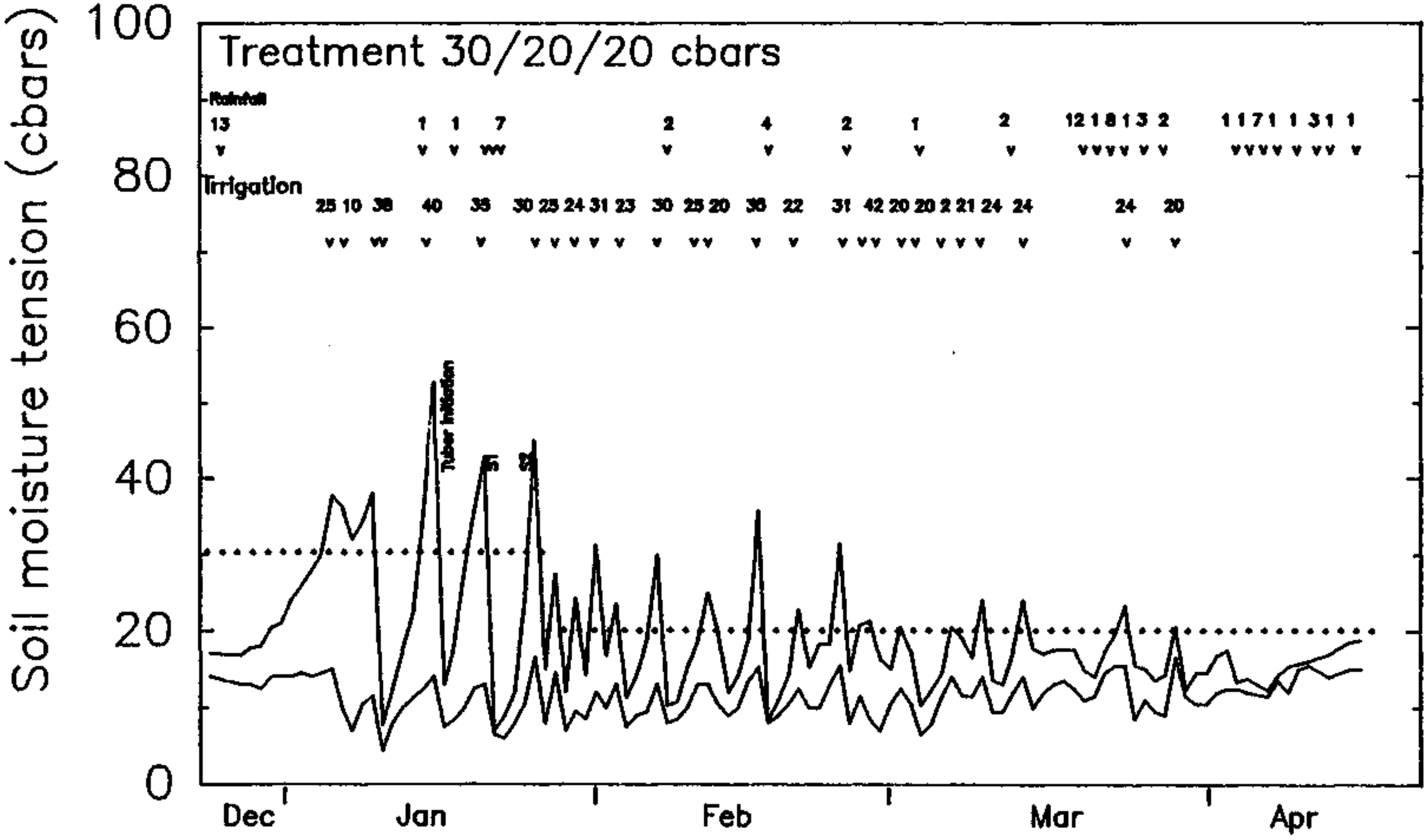
Treatment 6



APPENDIX 1 cont'

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

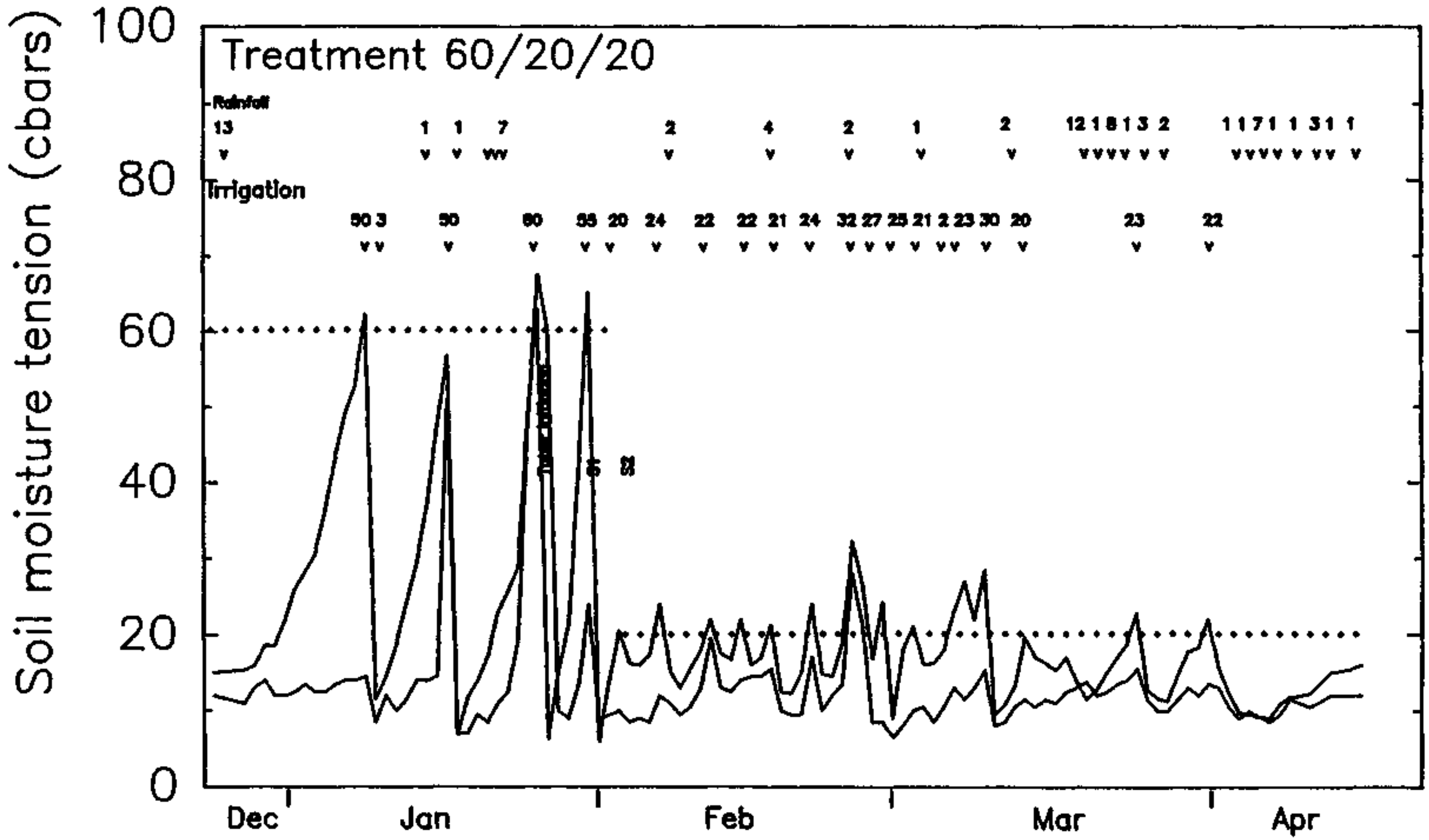
Treatment 7



APPENDIX 1 cont'

Changes in soil moisture tension with time in each irrigation treatment. Note: upper line in each plot shows readings from the tensiometer installed at 30 cm depth, and the lower line shows readings from the tensiometer installed at 60 cm.

Treatment 8



5.3 EFFECT OF IRRIGATION AT DIFFERENT SOIL WATER POTENTIALS ON THE YIELD AND QUALITY OF CADIMA AND KENNEBEC POTATOES *(Experiment 90MC33)*

Aim

The aim of this experiment was to test the tuber yield and quality response of Kennebec and Cadima potatoes to irrigation applied at different soil water potentials (SWP) and thus to set an initial SWP limit below which the soil should not be allowed to dry out when irrigating these varieties.

Materials and Methods

Site details

The experiment was conducted at the Manjimup Horticultural Research Centre (34°18' S, 116°7' E) during the 1990/91 season. The soil was a loamy sand over mottled clay at 70-80 cm (Dy 5.31, Northcote, 1974). Some of the relevant soil physical characteristics were presented previously (89MC18).

Experimental design and treatments

The experiment consisted of a randomised complete block arrangement of two varieties (Kennebec and Cadima) x four irrigation treatments. The irrigation treatments were based on soil water potential (SWP) measured at a depth of 30 cm below the top of the potato ridge. Sufficient water was applied at each irrigation to return the soil to field capacity when the SWP reached 15, 22, 30 or 40 centibars (cb). The treatments were arranged in four replications. Each plot consisted of 6 x 5.5m long rows, with a 0.5m buffer between plots. Row spacing was 0.8m. Soil water potential was measured in each plot using 'Irrometer' type tensiometers (Irrometer Company, Riverside, California, USA) placed between two average plants in the second row in from the northern edge of the plot. Readings were taken daily between 8.00 and 10.00am and the readings from the four replicates were averaged.

Water was applied to individual plots using plot irrigators, similar to those described by Riley and Wolfe (1958). Water quality was good (EC < 100mS/m).

Trial establishment

Prior to the experiment the site used had been in a pasture/lupins rotation for five years. Site preparation began six weeks before planting when the site was sprayed with glyphosate (3 L/ha Roundup®). The site was cultivated four weeks before planting using a mould-board plough. Fenamiphos (24L/ha Nemacur®) and chlorpyriphos (6L/ha Lorsban®), together with 200 kg/ha KCl, 100 kg/ha $MgSO_4$ and a trace element mix containing 15kg/ha Cu SO_4, 7.5kg/ha ZnO, 10kg/ha $MnSO_4$ and 15kg/ha Borax were applied four days before planting and incorporated with a roto-tiller. On 30 October, 1990, 3000 kg/ha of Potato E® fertiliser (3.5% N, 7% P, 6.6% K) was banded into ridges ready for planting. The experiment was planted on 1 November, 1990. 50g hand-cut seed pieces, which were dusted with tolclofos-methyl (2 kg/t Rizolex®), were planted by hand into the pre-formed hills at an in-row spacing of 0.2m (40,000 plants/ha) and 0.25m (50,000 plants/ha) for

Kennebec and Cadima, respectively. All plots were machine moulded three weeks after planting.

Soil moisture monitoring
In addition to the tensiometer at a depth of 30 cm, a second tensiometer was installed in each plot at 50 - 60 cm. This tensiometer provided a check on the adequacy of water applications. The soil moisture profile was measured periodically throughout the experiment using a neutron probe which had been calibrated on site. Total volumetric soil moisture (VSM) contents were calculated by integrating readings at depths of 20, 30, 40, 50, 60, 80 and 100 cm. This data provided a second check on the adequacy of water applications. Also, total consumptive water use (CWU) was estimated for each treatment from the water balance:

$$\text{CWU} = \text{VSM at emergence} - \text{VSM at harvest} + \text{applied irrigation} + \text{rainfall}$$

Drainage below 100 cm was assumed to be negligible.

Agronomic management
Additional nitrogen was applied post-emergence in two applications - 297 kg NH_4NO_3/ha on 28 November 1990 and 220 kg NH_4NO_3/ha on 19 December1990.
Metribuzin (750 mL/ha Sencor 480 SC®) was applied one weeks after emergence for annual weed control. Preventative control of fungal leaf diseases was achieved with weekly applications of either chlorothalonil (2 L/ha Bravo®) or iprodione (2 L/ha Rovral®) which began six weeks after emergence. Permethrin (150 mL/ha Ambush®) was used to control green looper and potato tuber moth and methamidophos (700 mL/ha Nitofol®) was used for control of aphids and potato tuber moth when necessary.

Plant sampling
Whole plant samples, consisting of 2 whole plants, were taken from an inside sampling row in each plot on 5 occasions during the crop growth period - 48, 63, 76, 90 and 103 days after planting. The samples were washed and separated into tubers, stems and leaves. The fresh weight of tubers was recorded. Tubers were then diced and all samples were dried at 70°C in a forced drought oven for 48 hours. Sample dry weights were recorded.

Harvest and grading
All plots were allowed to naturally senescence before harvest. 5 m lengths from two inside rows in each plot were harvested using a single row harvester on 25 March 1991. Within each plot all tubers with any greening or rots were counted and weighed separately. The remaining tubers were counted and weighed into the following size categories: <100g, 100-250g, 250-450g and >450g. Processing grade tubers were >100g and free of any defects.

Tuber quality assessment
Twenty tubers (>250g) were sliced longitudinally and inspected for hollow heart and other internal defects. Tuber specific gravity was measured on a 3.5 kg sample of 100-450g tubers from each plot using the weight in air - weight in water method (Redshaw and Fong, 1972). Within three weeks of harvest, a 13 mm French fry was cut longitudinally from the

centre of 10 tubers per plot. These were then cooked in palm oil at 180°C for 2 minutes and 45 seconds. Immediately after cooking, fry colour was assessed using a 1 to 7 colour scale, 1 being white and 7 dark gold, with a rating of 4 or less being acceptable. Also, the number of fries in each sample showing dark ends was recorded.

Statistical analyses
Data were analysed by analysis of variance using GENSTAT (GENSTAT 5 Committee 1987), and l.s.d.s ($P<0.05$) calculated for comparison of treatment means.

Results

Soil moisture tension, applied water and irrigation frequency
The actual mean SWP trigger points and the maximum SWP for each treatment during the experiment are detailed in Table 1. Irrigation was never applied until the designated treatment SMP was reached. The fact that tensiometer readings were recorded only once per day meant that the designated SWP trigger points were frequently exceeded. The maximum SWPs were recorded in each treatment during a hot two day period around 1 January 1991 when readings from the tensiometers were not recorded.

Table 1. Actual mean and maximum soil water potential (SWP) trigger levels for each treatment during the experiment.

Target SWP trigger point (-kPa)	Actual SWP trigger points			
	Mean		Maximum	
	Kennebec	Cadima	Kennebec	Cadima
15	17	18	27	22
22	25	23	39	30
30	34	33	54	52
40	46	45	63	61

Total applied irrigation water applied and irrigation frequency decreased as SWP decreased in both varieties (Table 2). Compared to -15 kPa, irrigating at -40 kPa more than halved the number of irrigation events for both varieties.

Table 2. Total water applied and number of irrigations for each treatment.

SWP trigger point (-kPa)	Total irrigation water (mm)		Number of irrigations	
	Kennebec	Cadima	Kennebec	Cadima
15	493	600	26	28
22	445	500	19	19
30	378	520	13	15
40	480	480	12	12

Growth periods
Irrigation treatments had little affect on the duration of growth in both varieties (Table 3). The -40 kPa treatment shortened the growth period of Cadima.

Yield
The total and processing tuber numbers and yields of both varieties were not significantly affected by irrigation treatments (Table 4). However, there was a significant ($p<0.05$) linear trend for increasing total and process yields with increasing SWP for Cadima potatoes.

Table 3. Average growth period for each variety and irrigation treatment.

SWP trigger point (-kPa)	Kennebec	Cadima
15	105	116
22	105	116
30	105	116
40	109	105

Table 4. Effect of soil moisture tension treatments on total and marketable tubers numbers and yields.

SWP (-kPa)	Total Yield (t/ha)		Total tuber No./plot		Marketable Yield (t/ha)		Marketable tuber number / plot	
	Ken	Cad	Ken	Cad	Ken	Cad	Ken	Cad
15	61.2	59.0	508	482	51.2	49.3	309	312
22	61.5	56.1	497	466	50.9	46.2	300	280
30	55.7	56.7	523	458	43.8	46.9	298	272
40	61.7	54.5	506	432	50.4	45.8	298	277
LSD (5%)	NS	NS	NS	NS	NS	NS	NS	NS

As with yields, average tuber weights and the distribution of tubers between various size ranges was not affected by irrigation treatments (data not shown). For Cadima, 66.5% and 29.5% and the processing tubers were in the 100-250g and 250-450g weight ranges, respectively. For Kennebec, the respective proportions were 71.9% and 25.2%.

Tuber quality
For both varieties there were no significant treatment effects on any of the measured tuber quality parameters. The average specific gravity of Kennebec and Cadima potatoes was 1.069 and 1.078, respectively. No significant tuber internal defects were found and the fry colour rating in all treatments from both varieties was 0 (top rating, light coloured).

Water use efficiency
Irrigation treatment had no significant effect on water use efficiency (WUE). However, the WUE of Kennebec (100 kg process yield/mm CWU) was significantly ($p<0.01$) higher than Cadima (82 kg process yield/mm CWU).

Plant growth

Plant growth data are shown in Figures 1 to 10. Overall, there were no significant treatments effects on the measured plant growth parameters, although on some sampling dates, significant differences were recorded between parameters in some treatments. For Cadima, the trend for decreased field tuber yield with decreased SWP was also evident in the total plant dry weight and tuber dry weight data at samplings from 76 days after planting. During the main tuber bulking period (76 - 90 days after planting) in both varieties, tuber yield (both fresh and dry) tended to be lower in the -40 kPa treatment, but at the final sampling there were no obvious treatment effects.

Discussion

The data presented here suggest that the tuber yield and quality of Kennebec and Cadima potatoes will be unaffected by an irrigation regime in which the SWP, measured at 30 cm depth, is allowed the fall to -40 kPa between irrigations throughout all growth stages. There is a need to test the response of these varieties to still lower SWPs.

Reference

Riley, J.P. and Wolfe, J.W. (1958). A field plot sprinkler irrigator. Misc. Paper No. 57. Agric. Experiment Station, Oregon State College, Corvallis.

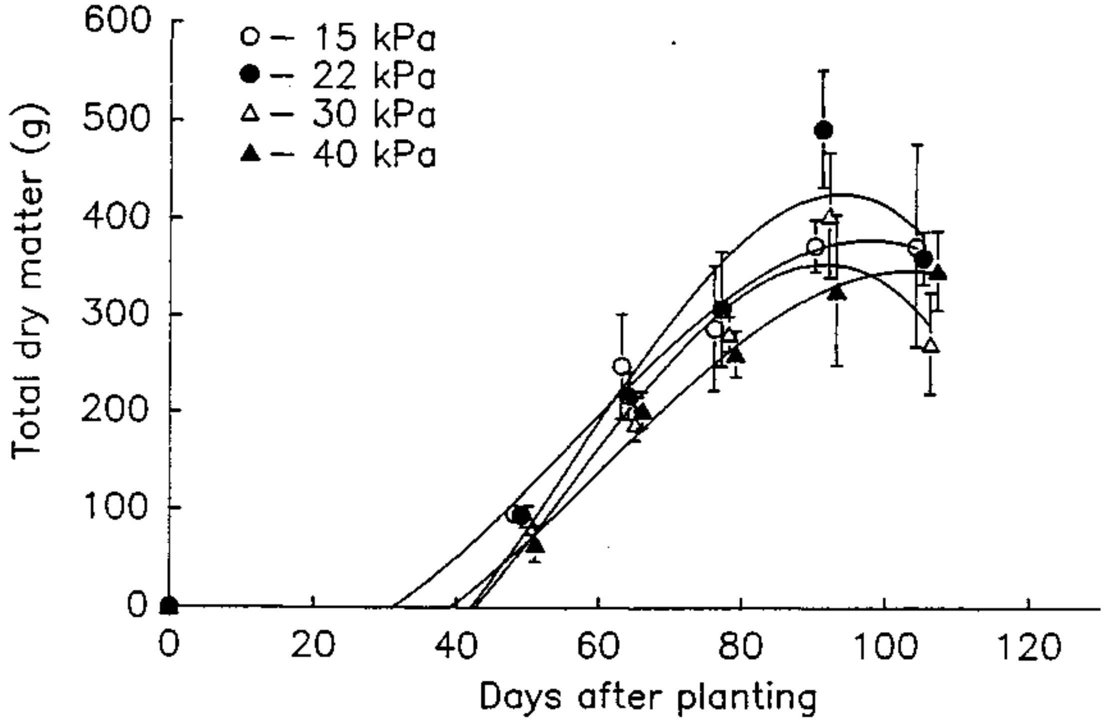


Figure 1. Total (tubers, stems and leaves) dry matter accumulation in Kennebec potatoes under four irrigation regimes. Vertical bars are standards errors.

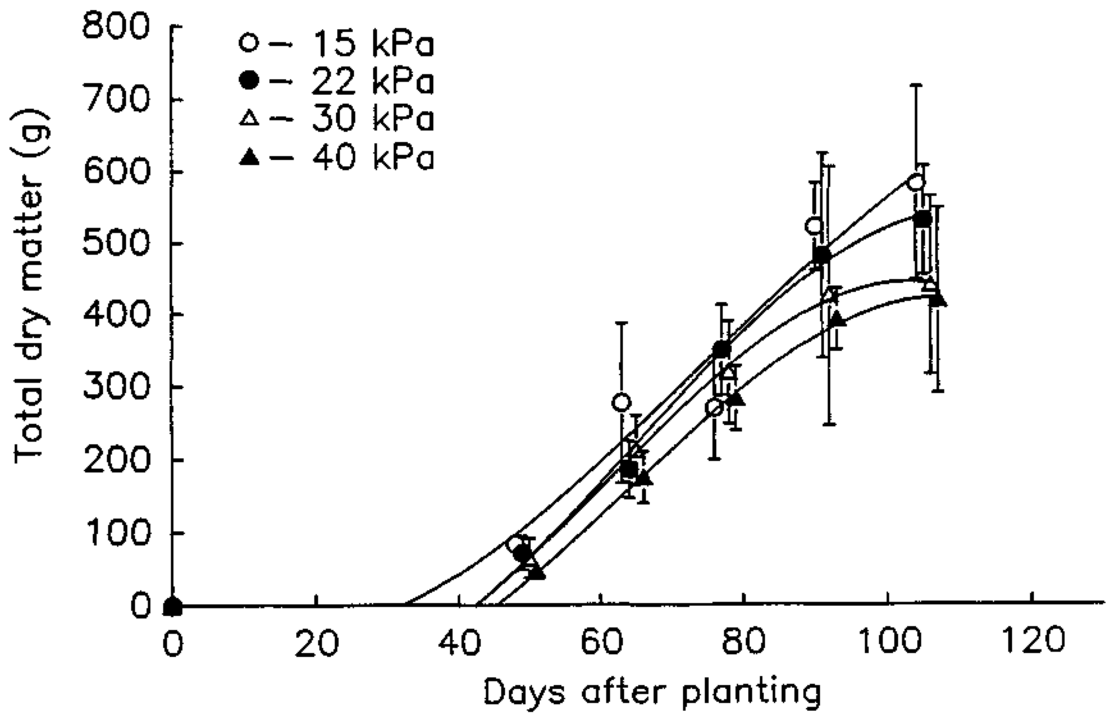


Figure 2. Total (tubers, stems and leaves) dry matter accumulation in Cadima potatoes under four irrigation regimes. Vertical bars are standard errors.

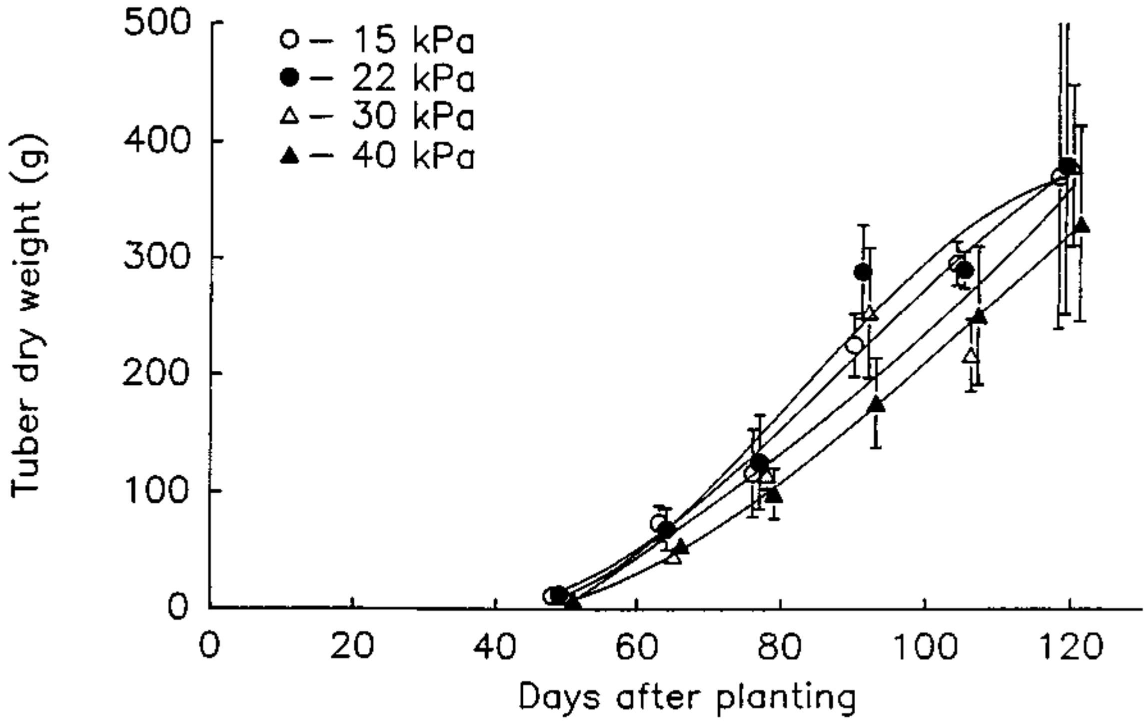


Figure 3. Tuber dry matter accumulation in Kennebec potatoes under four irrigation regimes. Vertical bars are standard errors.

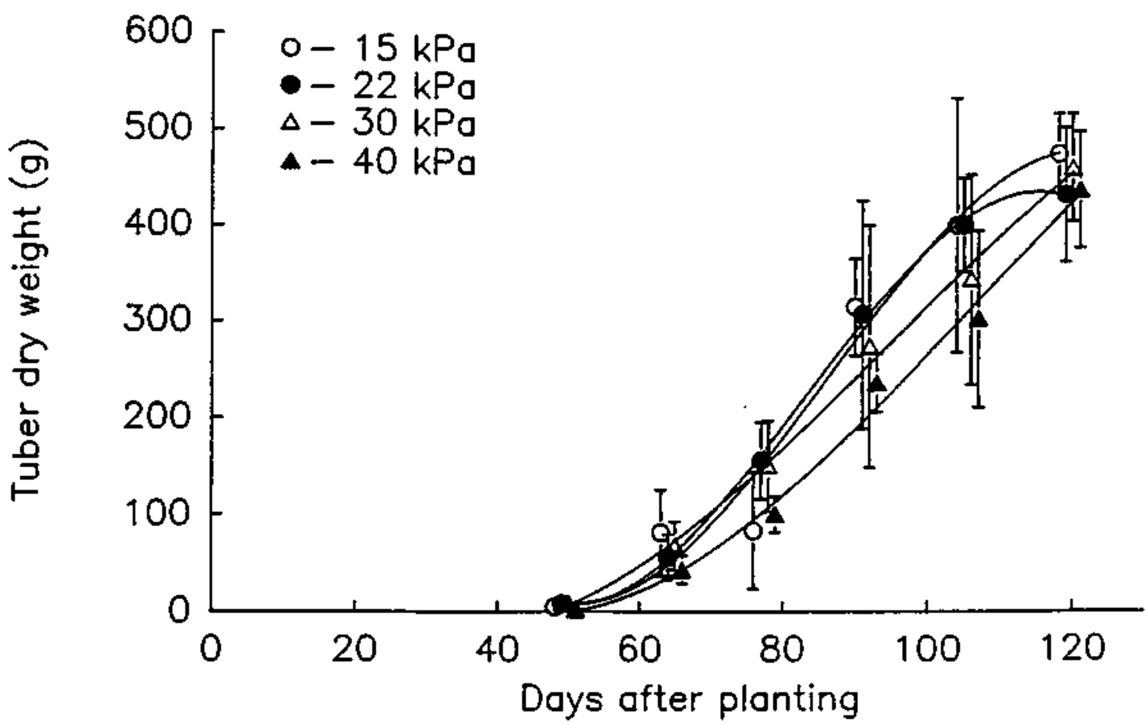


Figure 4. Tuber dry matter accumulation in Cadima potatoes under four irrigation regimes. Vertical bars are standard errors.

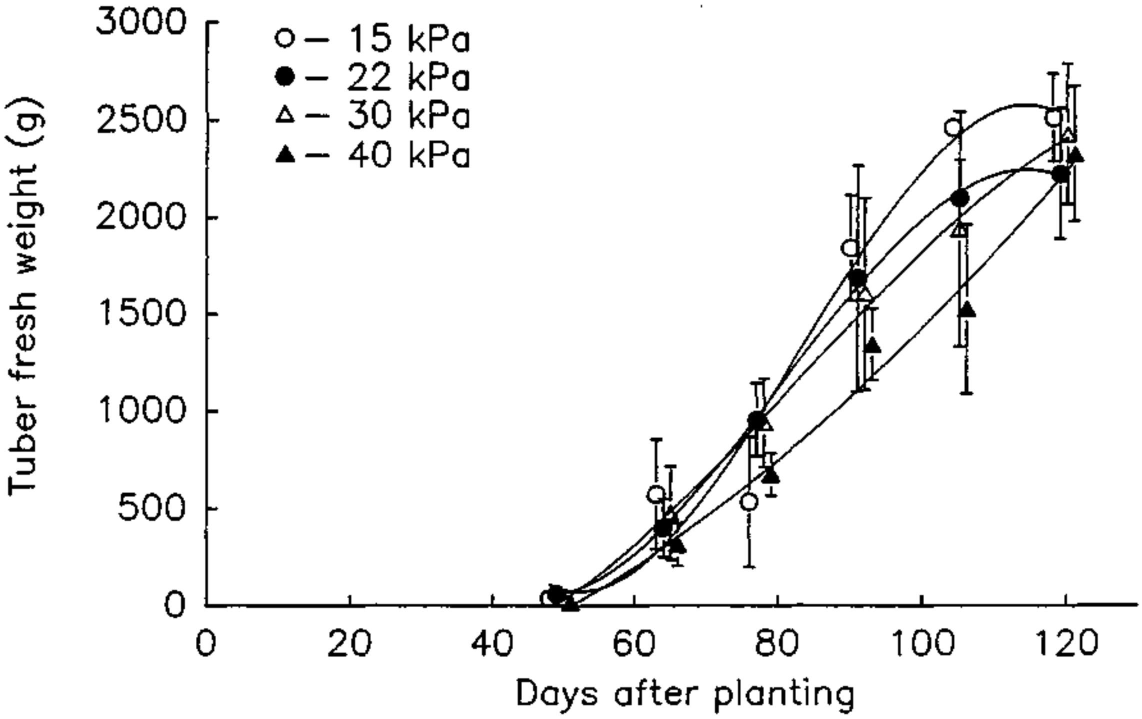


Figure 5. Tuber fresh weight accumulation in Kennebec potatoes under four irrigation regimes. Vertical bars are standard errors.

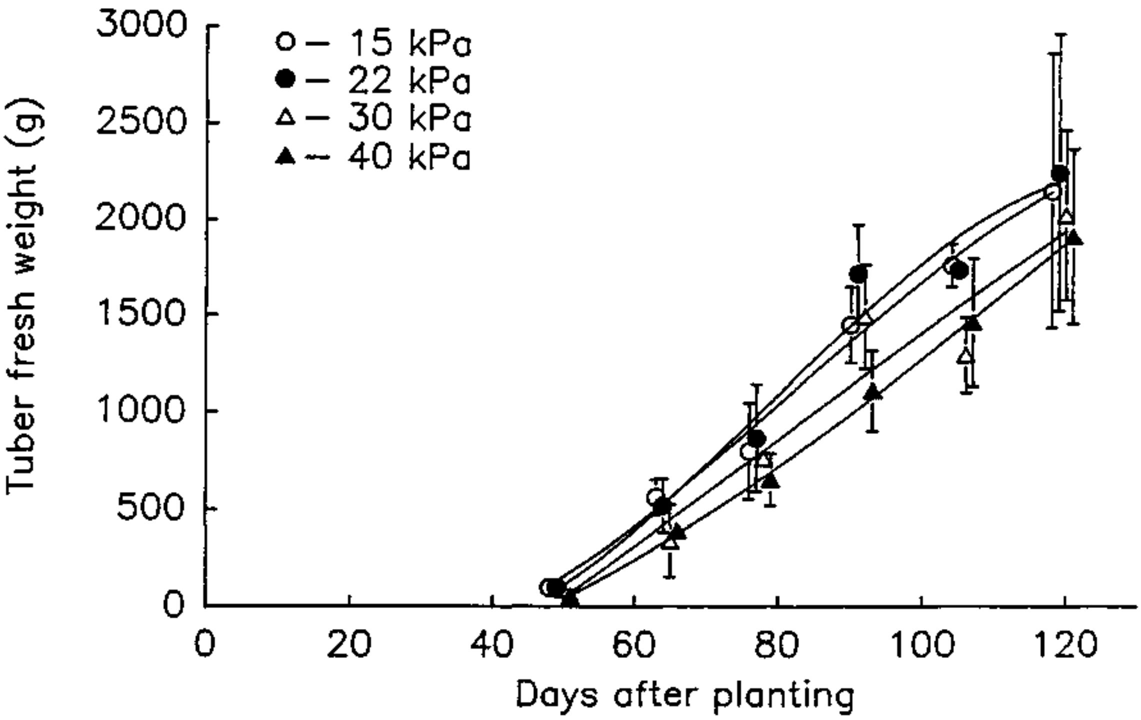


Figure 6. Tuber fresh weight accumulation in Cadima potatoes under four irrigation regimes. Vertical bars are standard errors.

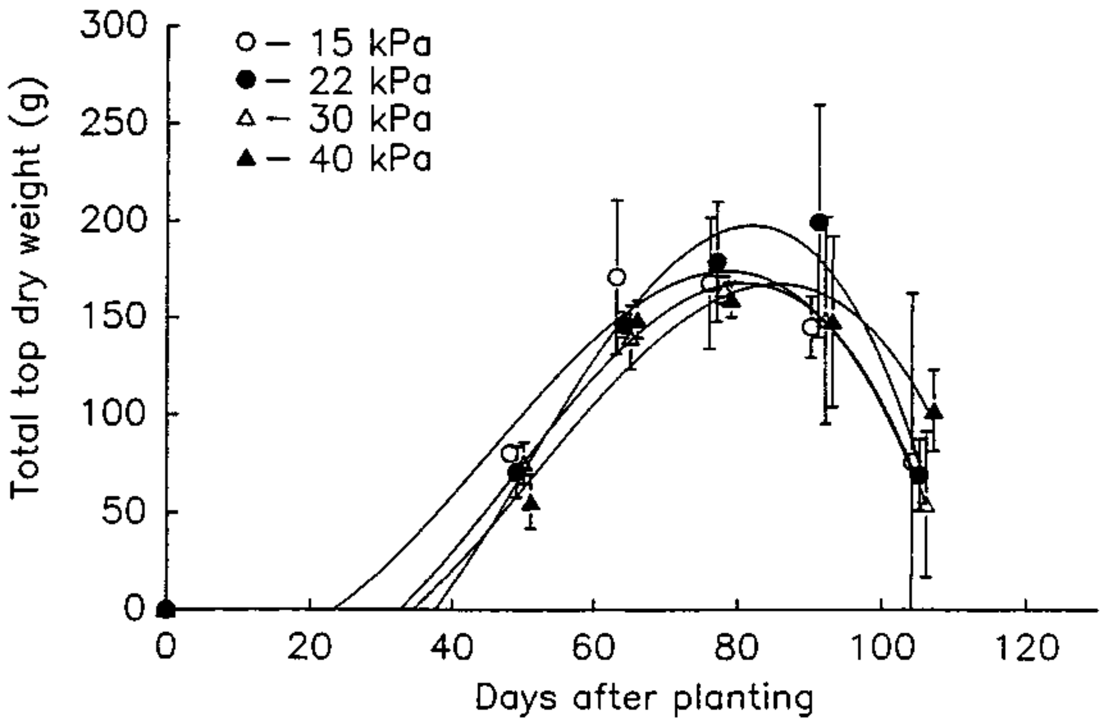


Figure 7. Total top (stem plus leaves) dry matter accumulation in Kennebec potatoes under four irrigation regimes. Vertical bars are standard errors.

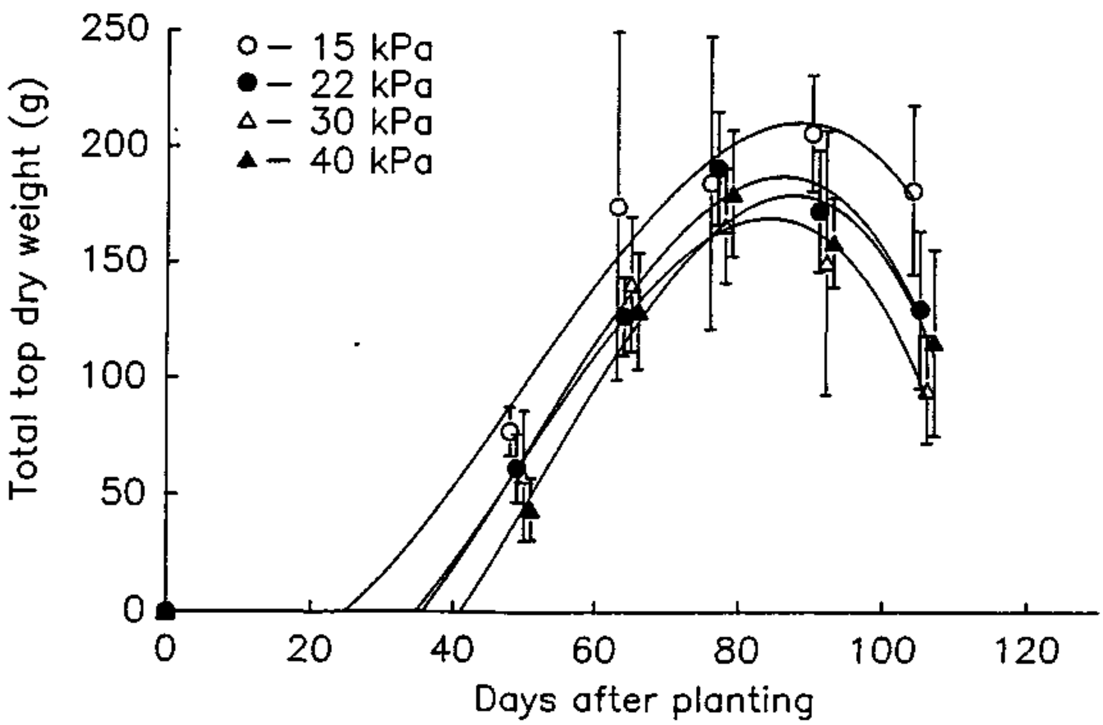


Figure 8. Total top (stem plus leaves) dry matter accumulation in Cadima potatoes under four irrigation regimes. Vertical bars are standard errors.

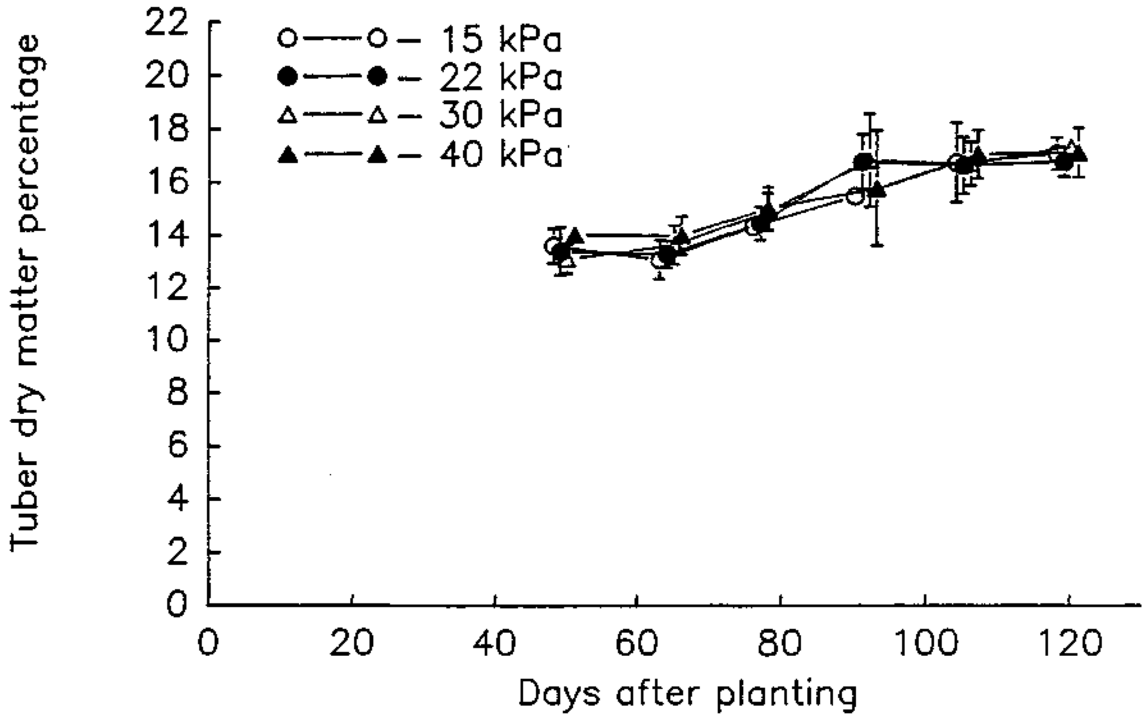


Figure 9. Tuber dry matter percentage with time after planting in Kennebec potatoes grown under four irrigation regimes. Vertical bars are standard errors.

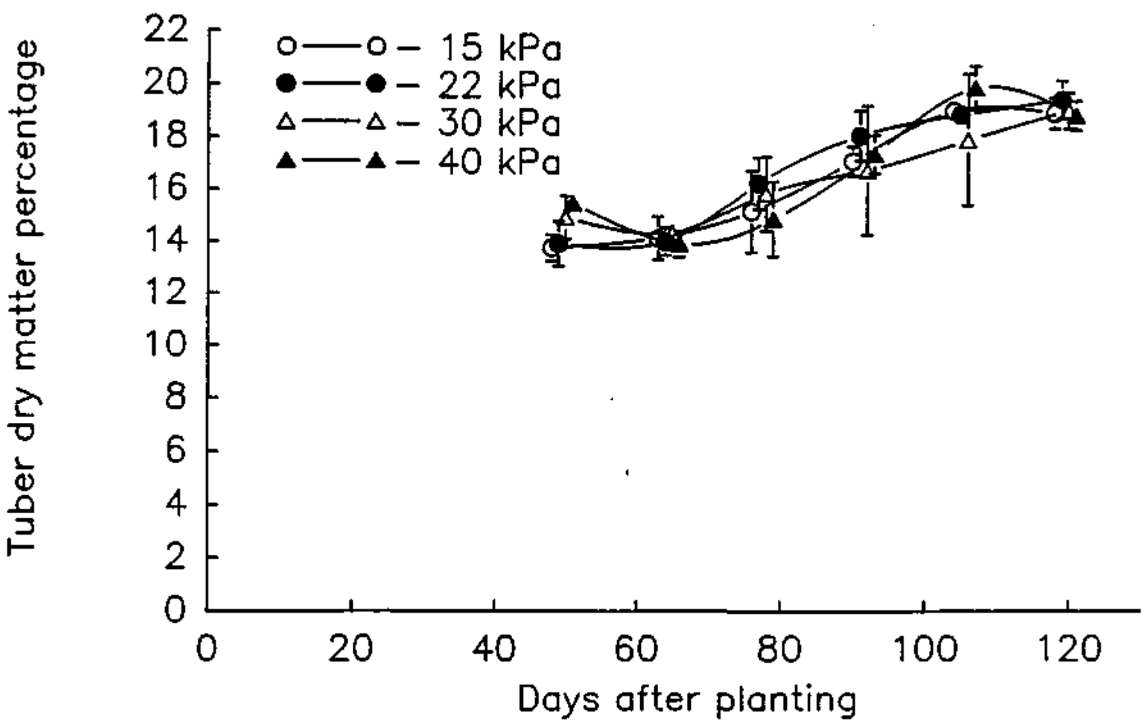


Figure 10. Tuber dry matter percentage with time after planting in Cadima potatoes grown under four irrigation regimes. Vertical bars are standard errors.

6.0 IRRIGATION AND NITROGEN MANAGEMENT OF RUSSET BURBANK POTATOES

M.A. Hegney and H.P. Hoffmann

Summary

Russet Burbank is the preferred potato variety for the production of French fries in Western Australia. Overseas experience has shown that this variety is among the most sensitive to water stress. Leading up to 1991, growers in the Manjimup-Pemberton area had had difficulty producing high processing yields of this variety using traditional irrigation and nitrogen management practices.

Experiments were conducted to determine the total water and nitrogen requirements of Russet Burbank potatoes grown under Western Australian conditions, and to define the soil moisture limits within which Russet Burbank potatoes needed to be irrigated to achieve maximum yield and tuber quality.

Major results

- Total and processing yield of Russet Burbank potatoes, grown on sandy loam soil, increased linearly in response to increasing level of irrigation water applied up to approximately 470mm, and to increasing consumptive water use (soil moisture at emergence - soil moisture at harvest + irrigation + rainfall) up to approximately 610mm.
- On a sandy loam soil type, there was no significant interaction between irrigation and nitrogen level in terms of their effect on tuber yield.
- A combination of high nitrogen level (600 kg/ha) and high irrigation level (125% of estimated evapotranspiration) caused a significant reduction in processing yield.
- On a sandy loam soil type, the optimum total nitrogen level for mid November planted Russet Burbank potatoes was found to be between 335 and 375 kg N/ha.
- Tensiometers were found to be a useful tool for monitoring changes in soil moisture level and scheduling irrigations in Russet Burbank crops. Based on readings from tensiometers installed at a depth of 30cm below the top of the final ridge, the highest total and processing yields, and lowest level of tuber malformations were obtained by irrigating at a soil water potential (SWP) of -20 kPa during all growth stages. However, it was also found that, provided the SWP was maintained above -20 kPa between emergence and early tuber growth, allowing the SWP to decline to -40 kPa during later growth stages had no detrimental affect on tuber yield or quality. This latter regime did not result in any water saving, but significantly reduced the total number of irrigation events during the life of the crop. Allowing the SWP to decrease below -40 kPa in the period between emergence and early tuber growth resulted in a significant increase in the proportion of malformed tubers.
- Effects of different irrigation regimes on tuber specific gravity were generally small. Tuber specific gravity tended to decrease with increasing levels of total nitrogen applied.

Recommendations

(a) *Extension/adoption by industry*

The results from these field experiments were presented to Western Australian potato growers at seminars in September 1990, August 1991, June 1992 and September 1996. Several publications were also produced. These included two articles in the "Potato Grower" magazine, a Farmnote on the use of tensiometers for scheduling irrigation in potato crops, and two Technotes produced as part of a production manual for growers producing processing potatoes for the then Edgell-Bird Eye company (now Simplot (Aust.)).

Following this research, the Edgell-Bird Eye company subsidised the purchase price of tensiometers for all of their processing potato growers and continue to provide their growers with assistance to set-up and monitor tensiometers. As a consequence, in 1995, the company estimated that 85% of their Russet Burbank potato growers in the Manjimup-Pemberton area made use of tensiometers for irrigation scheduling.

(b) *Directions for future research*

The results presented here provide a good foundation on which to base irrigation scheduling in Russet Burbank potato crops. They also provide a preliminary estimate of the nitrogen requirements of this potato variety when grown on sandy loam soils in the Manjimup-Pemberton area of Western Australia. However, particularly in the area of irrigation scheduling and its effect on tuber internal quality, further work is required. For instance, the effects on internal tuber quality of maintaining different levels of soil moisture around the time of tuber formation and during early tuber growth need to be further investigated.

There is trend in Western Australia for increased levels of processing potato production on lighter textured (sandier) soils than those studied here. The irrigation requirements of Russet Burbank and other potato varieties on these soil types needs to be determined. As it is more likely that there will be a significant interaction between irrigation and nitrogen management on sandier soils, these factors should be examined together.

(c) *Financial/commercial benefits*

Irrigation management is a critical factor determining the yield and quality of Russet Burbank potatoes. This work has already contributed to an improvement in Russet Burbank production levels and grower profitability in the Manjimup-Pemberton area of Western Australia.

6.1 EFFECT OF EVAPORATION REPLACEMENT RATE AND NITROGEN RATE ON THE YIELD AND QUALITY OF RUSSET BURBANK POTATOES. (*Experiment 89MC19)*

Introduction

The potato crop is commonly accepted as being shallow-rooted and more sensitive to water stress than many other crops (Singh, 1969; Epstein and Grant, 1973). As a result, in semi-arid regions, such as Western Australia, irrigation is an essential component of commercial potato production systems.

The potato cultivar 'Russet Burbank' is used extensively around the world for french fry production, and has become important in the potato processing industry in Western Australia. Overseas experience has shown that this cultivar is more sensitive to water stress than other cultivars (Millar and Martin, 1983).

In developing irrigation management guidelines for potatoes produced in Western Australia, it was considered important to establish water production functions for the crop as a basis on which to assess and refine alternative irrigation management techniques. Various workers have found linear relationships between water applied and yield for potatoes (Shalhevet *et al.*, 1983; Hane and Pumphrey, 1984; Martin *et al.*, 1992). Total seasonal water use for Russet Burbank potatoes has been found to vary between 450 mm and 700 mm (Wright and Stark, 1990), depending on season and region of production.

Nitrogen is also an important factor affecting potato yields both in Australia (Laurence *et al.*, 1985) and worldwide (Perrenound, 1983). The interaction between irrigation and nitrogen in terms of potato crop response is well recognised (Middleton *et al.*, 1975; Ojala *et al.*, 1990). Given this interaction, it was considered important at the beginning of this project to examine the magnitude of any interaction between nitrogen and irrigation for potatoes grown on sandy loam soils. Also, an indication of the total nitrogen requirement of Russet Burbank potatoes grown under Western Australian conditions was required in order to ensure adequate levels were supplied in any future work. Overseas research has shown that the total nitrogen requirement of Russet Burbank potatoes varies between 200 and 400 kg N/ha (Westermann and Kleinkopf, 1985; Lauer, 1986a; Roberts and Cheng, 1988).

Aims

The objectives of this experiment were (1) to determine the water production function for Russet Burbank potatoes produced in Western Australia, (2) to determine the extent of any interaction between irrigation and nitrogen rates, and (3) to determine the optimum nitrogen application level for Russet Burbank potatoes on a sandy loam soil.

Materials And Methods

Site details

The experiment was located at the Manjimup Horticultural Research Centre (34° 18' S, 116° 7' E) on a sandy loam soil with gravel over clay at about 0.5 m. Some of its relevant physical characteristics are given in Table 1.

Table 1. Soil characteristics of experimental site.

Soil Depth (cm)	Field Capacity (% vol.)	Wilting Point (% vol.)	% Gravel	% Course Sand	% Fine Sand	% Silt	% Clay	pH (H_2O)
0 - 50	20	10.9	31.8	37	40.6	0.2	13.2	5.9
50 -80	25	12.4	29.2	29	39.8	7.8	24.0	6.0

Experimental design and treatments

Differential irrigation treatments were imposed from the time of tuber initiation until crop maturity using a single line-source sprinkler arrangement as described by Hanks *et al.* (1976). The sprinkler line, with sprinklers 6.0 m apart, was placed parallel to the row direction in the middle of the field. Each sprinkler head (Pope Premier®), with a 4.8 x 2.4 mm nozzle combination, was operated at 280 kPa (40 psi) of pressure. The application rate was uniform down each row but decreased almost linearly across the field, from 16 mm/hr at the sprinkler line to a negligible amount at the edge of the experimental area, about 13 m from the line-source.

15 rows of potatoes were planted on each side of the line-source. Six rows on each side were selected as irrigation treatment locations (row numbers 3, 5, 7, 9, 11 and 13 from the sprinkler line, with the highest irrigation rate being received at row 3). Hereafter, these row numbers will be called I6, I5, I4, I3, I2 and I1, respectively.

Six nitrogen rates (0, 50, 100, 200, 400, 600 kg N/ha total) were imposed in 7.0 m wide strips at right angles to the line-source. The nitrogen treatments were randomised within four replications, two on each side of the line-source. The nitrogen treatments were considered as main plots and the irrigation levels as subplots. Subplots were one row wide by 7 m long. The nitrogen was applied as NH_4NO_3 hand topdressed along each row in three equal applications - at planting, 7 days after first emergence (DAE)(5 December) and 30 DAE(5 January 1990).

Site preparation

A non-experimental oat crop was grown on the trial site in the previous season. Site preparation began when residual crop and weeds were sprayed with glyphosate (3 L/ha Roundup®) on 10 August, 1989. The area was ploughed on 17 August and then cultivated with a roto-tiller on 6 October. Fenamiphos (24 L/ha Nemacur 400®) and chlorpyriphos (6 L/ha Lorsban 500®), together with 265 kg K/ha and a trace element mix containing 15 kg/ha $CuSO_4$, 7.5 kg/ha ZnO, 10 kg/ha $MnSO_4$, 15 kg/ha Borax and 50 kg/ha $MgSO_4$, were applied on 8 November and incorporated with a roto-tiller.

Crop management

Certified seed tubers which had been harvested the previous autumn and held in cool store at 4°C, were removed from storage on 16 October. They were held at ambient temperature, to allow sprouting, until 8 November when they were cut to *c.* 50 g sets and dusted with tolclofos-methyl fungicide (2 kg/t Rizolex®).

Furrows, 0.8 m apart were created by machine on 9 November. Superphosphate at 275 kg P/ha and one third of the total nitrogen allocation for each treatment was hand banded along the bottom of the furrows. This fertiliser was covered by hand with approximately 50 mm of soil. Sets were then placed by hand at 0.35 m apart along each furrow on 10 November, to give a population density of 35,700 plants/ha. Nitrogen treatment plots within a row were seperated by four plants of a red-skinned variety (cv. Desiree). The furrows were then filled and moulded by machine. All plots were again machine moulded on 5 December when 50% of plants had emerged.

Paraquat plus diquat (1.0 L/ha Sprayseed®) was applied on 29 November for general weed control. Regular sprays of chlorothalonil (2 L/ha Rover®) and iprodione (2 L/ha Rovral®) were applied to control early blight (*Alternaria solani*) and methamidophos (700 mL/ha Nitofol®) and permethrin (150 mL/ha Ambush®) were applied to control potato tuber moth, aphids and caterpillars. Fenitrothion (1 L/ha Fenitrothion 500®) was applied once to control wingless grasshoppers.

Irrigation management

Between planting and when the line-source was first brought into operation on 5 January 1990 (30 days after emergence, DAE), the entire site was irrigated uniformly to replace 100% of estimated ET whenever 20 - 25 mm of pan evaporation (Ep) had accumulated. Throughout the experiment, ET was estimated by ET = K.Ep. The values of K that were used are shown in Table 2. The line-source was operated until 50% crop senescence (19 March 1990). During the operation of the line-source, the crop was irrigated so that irrigation treatment 4 (I4) received 100% of ET whenever 20 - 25 mm of pan evaporation had accumulated. The water applied to each subplot was measured with raingauges following each irrigation. Irrigations were conducted only under calm conditions to avoid distortion of the water distribution pattern. Irrigation water quality was good with an EC of less than 100 mS/m.

Table 2. K values used to estimate evapotranspiration (ET).

Date	K value
05/12/89 - 04/01/90	0.5
05/01/90 - 11/01/90	0.5
12/01/90 - 23/01/90	0.8
24/01/90 - 01/03/90	1.0
02/03/90 - 19/03/90	0.9

Petiole analysis

On three occasions during the growth of the crop (18 January, 1 February and 20 February; 43, 57 and 78 DAE respectively) twenty petioles from youngest fully emerged leaves (P-YFEL) were sampled from the treatment rows. At the first sampling, the length of the longest tuber on plants in 200 kg N/ha plots was 15-20mm. The petioles were dried at 70°C for 48 hours and forwarded to CSBP & Farmers Ltd. Laboratories, Bayswater, W.A., for analysis of NO_3-N (ppm) and total nitrogen (%).

Harvest and Tuber Assessment

The experiment was harvested after complete plant senescence using a single row harvester. Tubers from each plot were counted and weighed into the following size categories: 0-100g, 100-250g, 250-450g and >450g. Processing grade tubers were >100g and free from obvious defects such as greening, rots or severe secondary growth (tubers with minor second growth, such as bud swelling, were classed as processable; tubers with growth cracks were also considered processable). Tubers showing growth cracks or secondary growth were counted and weighed seperately. Specific gravity was determined on a 3.5 kg sample of tubers weighing between 250 and 450g from each plot using the weight in air - weight in water method.

Data analyses
Data were analysed by analysis of variance using GENSTAT (GENSTAT 5 Committee 1987), and l.s.d.s ($P<0.05$) calculated for comparison of treatment means. Linear and quadratic regression functions were fitted to yield data in response to water applied and petiole nitrate levels.

Results

Water application
Between emergence and the start of line-source irrigation the experiment was irrigated 8 times applying a total of 96 mm water. 22 mm of rain was received during this period. During the period of line source irrigation, the experiment was irrigated 17 times. At the end of the line-source irrigation period, the wettest treatment (I6) had received 125% ET, while the driest treatment (I1) had received only 60% (Table 3). Total pan evaporation for the period between emergence and 50% senescence was 631mm.

Duration of growth
Nitrogen rates lower than 200 kg/ha reduced the period between planting and 90% crop senescence by 10 to 20 days (Table 4). The crop growth period was also reduced by low irrigation rates (I2 and I1).

Table 3. Water applied and percent estimated ET for each irrigation treatment for various periods during crop growth[1].

Irrigation Treatment	Irrigation + Rainfall (mm) A to B	Irrigation (mm) B to C	Rainfall (mm) B to C	Total Water Applied (mm) B to C	Percent Estimated ET B to C	Total Water Applied (mm) A to C	Percent Estimated ET A to C
I6	118	369	64	433	119	551	125
I5	118	336	64	400	110	518	118
I4	118	288	64	352	96	470	107
I3	118	222	64	286	78	404	92
I2	118	142	64	206	56	324	74
I1	118	81	64	145	40	263	60

1. A = 100% emergence, B = start of line-source irrigation, C = 50% crop senescence.

Table 4. Effect of nitrogen and irrigation treatments on the number of days between planting and 90% senescence.

Irrigation	Nitrogen Treatment (kg/ha)						
Treatment	0	50	100	200	400	600	Mean
I6	120	124	124	133	136	140	129.5
I5	120	124	124	133	136	140	129.5
I4	117	124	124	133	136	140	129.0
I3	117	117	111	133	136	140	125.7
I2	111	111	111	133	136	130	122.0
I1	103	103	103	124	124	126	113.8
Mean	114.7	117.2	116.2	131.5	134.0	136.0	

Total and processing yield

Total and processing yield increased as both nitrogen and irrigation rate increased (Figure 1). At high irrigation rates (I4, I5, I6), the 600 kg/ha nitrogen rate caused a yield decline. In this experiment all of the nitrogen was applied very early in the life of the crop. When combined with adequate water rates, the 600 kg/ha nitrogen rate caused a delay in plant emergence and reduced early crop growth.

Statistical analysis of the total and processing yield data are presented in Table 5. The single line-source arrangement of this experiment did not allow complete randomization of irrigation treatments. Comparison between nitrogen rates and nitrogen x irrigation interactions can be made (Hanks *et al.*, 1980), but analysis of the irrigation effects is not strictly valid. Clearly, the yield response to nitrogen rates was highly significant. The yield data for the nitrogen main effect is shown in Table 6. The response functions fitted to this data (Eq. 1 & 2) gave an optimum nitrogen rate of 375 kg N/ha. If the nitrogen data from the three highest irrigation treatments only (I4, I5, I6) is considered, the optimum nitrogen rate falls to 335 kg N/ha (Eq. 3).

Total yield response to nitrogen (main effect):

$$y = 49.53+0.064x-0.000845x^2,\ r^2=0.975 \qquad (1)$$

Processing Yield response to nitrogen (main effect):

$$y = 40.52+0.071-0.000097x^2,\ r^2=0.967 \qquad (2)$$

Total yield response to nitrogen (I4+I5+I6):

$$y = 56.56+0.096x-0.000143x^2,\ r^2=0.986 \qquad (3)$$

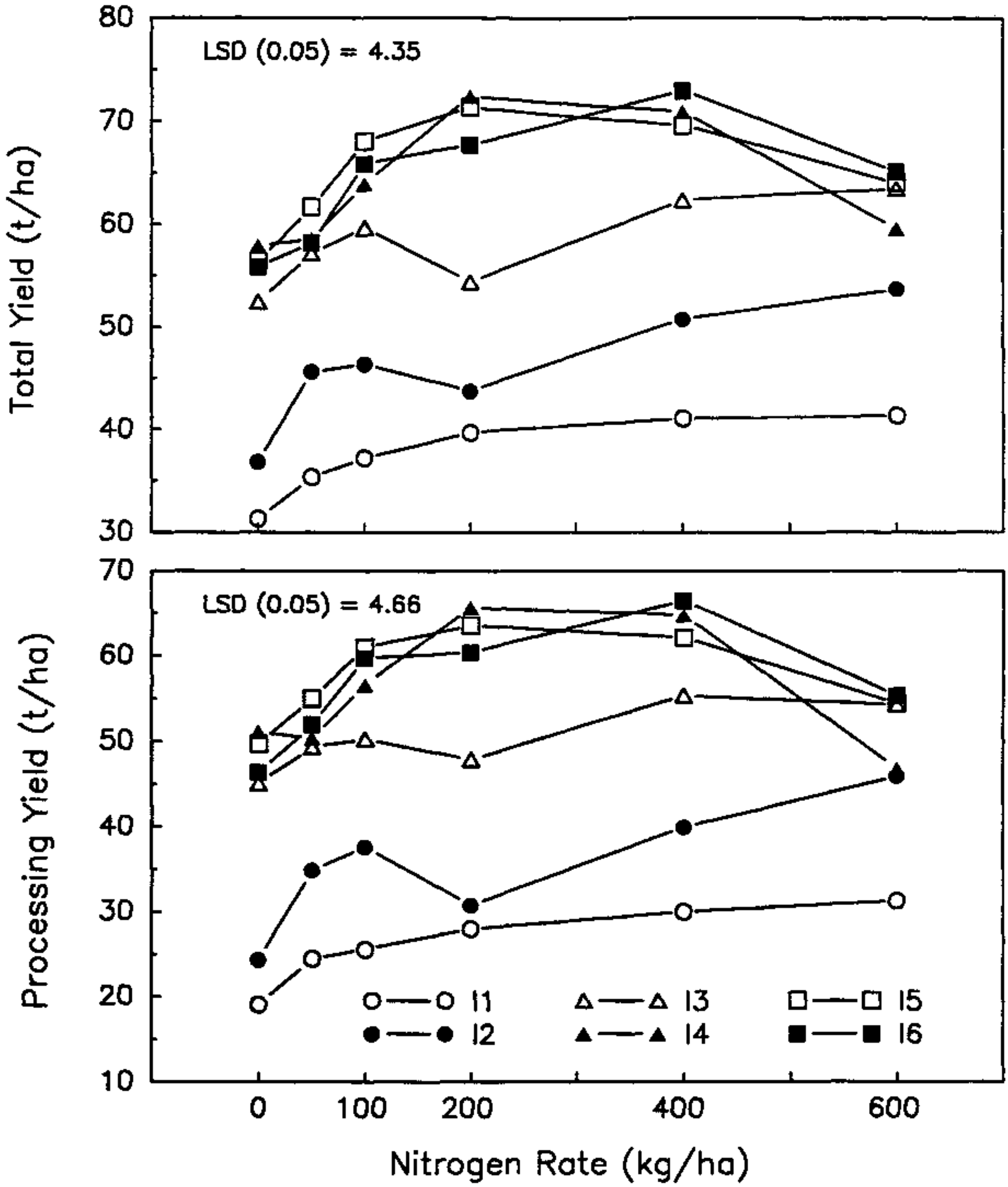


Fig. 1 Total and processing yield response of Russet Burbank potatoes to nitrogen and irrigation rates. LSD's are for the nitrogen main effect.

For total yield, there was no significant interaction between nitrogen and irrigation rate. For processing yield, the interaction was significant ($p<0.05$) suggesting that the toxic effects of the 600 kg N/ha rate at high irrigation rates reduced the proportion of processable tubers.

Table 5. Analysis of variance - mean square values for total and processing yield.

Source of Variation	df	MS-Total Yield	MS-ProcessingYield
Total (subplots)	143		
Main Plot			
Blocks, R	3	163.79	255.49
Nitrogen, N	5	499.55b	546.34b
Error (a)	15	53.22	61.25
Irrigation, I	5	3138.88b	4095.87b
N x I	25	44.09	77.49a
Error, (b)	90	32.4	38.96

a. significant at 5% level, b. significant at 1% level.

Table 6. Effect of nitrogen rate on total and processing yield (means of all irrigation rates)

Nitrogen Rate (kg/ha)	Total Yield (t/ha)	Processing Yield (t/ha)
0	48.5	39.3
50	52.8	44.4
100	56.9	48.5
200	58.2	49.4
400	61.3	53.2
600	57.9	48.1
LSD ($p<0.05$)	4.4	4.7

As shown in Figure 1 and Table 6, there was no significant difference between yields at 200 and 400 kg N/ha. Therefore, the irrigation response data from these treatments was combined to produce the relationship between total and processing yield and water application levels shown in Figure 2. Total and processing yield increased linearly as total water application increased from 263 to 470mm (60 to 107% ET). Optimum yield occurred at a total water application level of *c.* 475mm. At higher water application levels yield remained unchanged. Irrigation levels had no effect on the proportion of total yield that was processable.

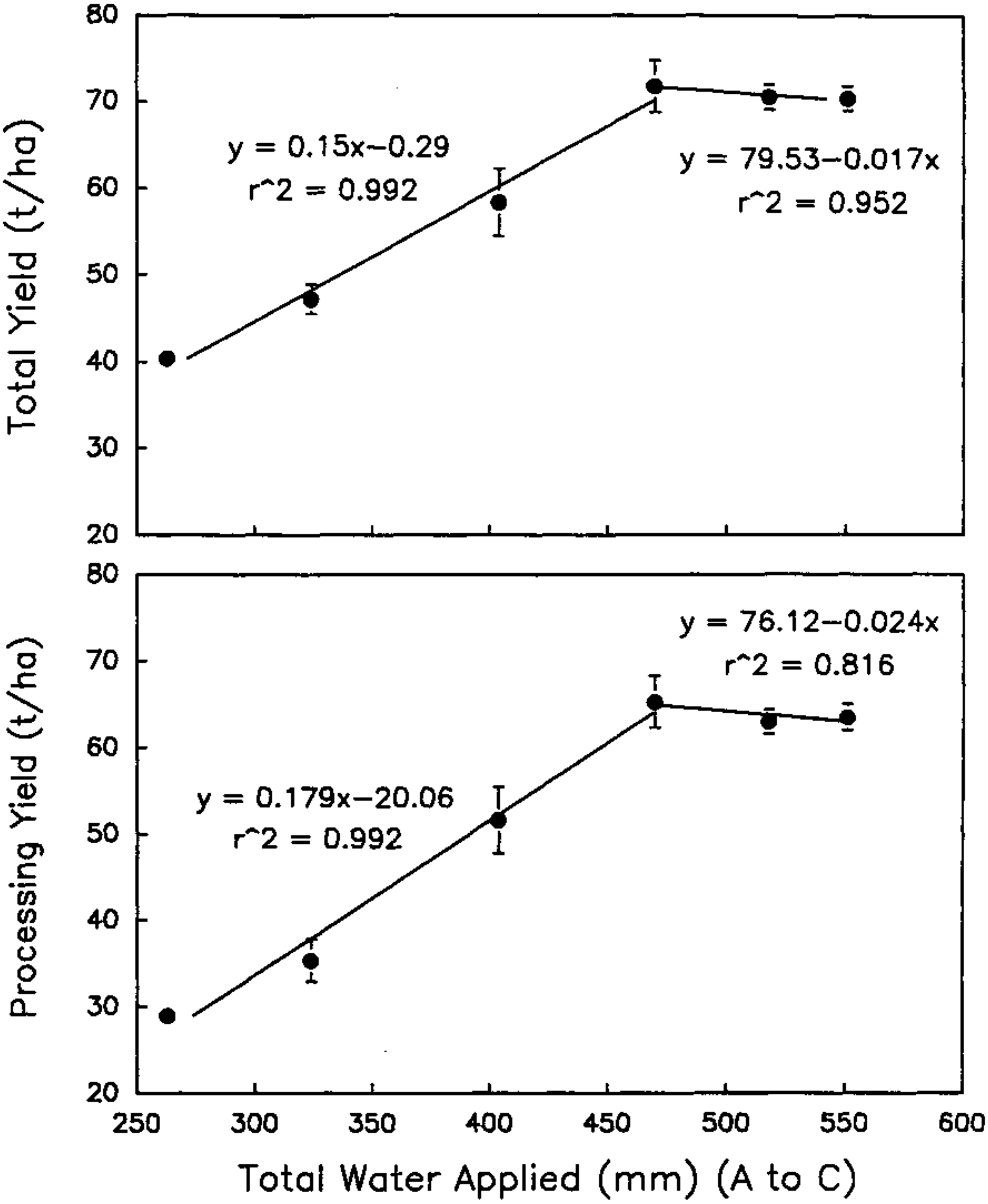


Fig. 2 Total and processing yield response of Russet Burbank potatoes to total amount of water applied (irrigation plus rainfall) between the start of line-source irrigation (B) and 50% crop senescence (C).

Yield components

Nitrogen and irrigation rates had no affect on tuber numbers per plant. Yield responses to both nitrogen and irrigation resulted from increases in average tuber weight (Table 7)(Appendix 1). The yield of tubers weighing less than 100g was not affected by nitrogen rate, but decreased with increasing irrigation rates (Appendix 2). The most significant yield increases in response to both nitrogen and irrigation were in the 250-450g and >450g tuber weight ranges.

Table 7. Main effects of nitrogen and irrigation rate on average tuber weight and average processing tuber weight.

	Average tuber weight (g)	Average processing tuber weight (g)
Nitrogen Rate (kg/ha)		
0	133	175
50	142	182
100	151	193
200	157	203
400	164	215
600	157	215
LSD ($p<0.05$)	14	13
Irrigation Treatment		
I1	108	164
I2	125	173
I3	156	202
I4	169	213
I5	175	217
I6	171	214

Tuber Quality

Tuber specific gravity decreased significantly when the nitrogen rate increased up to 200 kg/ha (Figure 3). Specific gravity did not decrease further at higher nitrogen rates. At the lowest irrigation rate, specific gravity was higher than at all other irrigation rates.

The proportion of tubers with growth cracks or second growth increased significantly at nitrogen rates of 400 and 600 kg/ha (Table 8). The proportion of tubers with growth cracks showed a decreasing trend with increasing irrigation, while the proportion of tubers with second growth appeared to be unaffected by irrigation rate. There was no significant interaction between irrigation and nitrogen rate with respect to these tuber malformations.

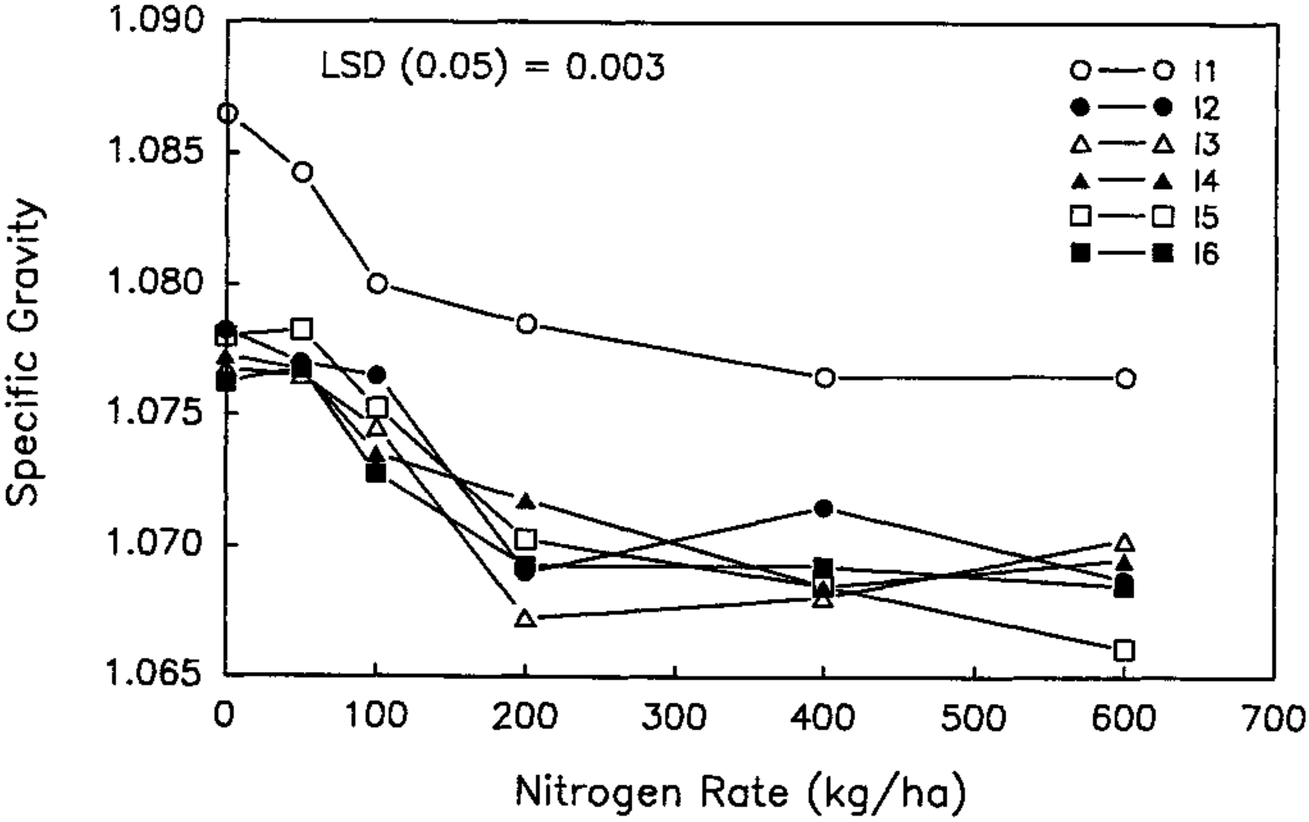


Fig. 3 **The response of tuber specific gravity to nitrogen rates and irrigation treatments. The LSD is for the nitrogen main effect.**

Table 8. Main effects of nitrogen and irrigation rate on the proportion of total yield comprised of tubers with growth cracks and second growth (knobs).

	Growth Cracks (%)	Second Growth (%)
Nitrogen Rate (kg/ha)		
0	0a	3.5a
50	0.1a	3.0a
100	0.2a	5.1a
200	0.1a	6.1a
400	1.4b	8.5a
600	3.9c	11.8b
Irrigation Treatment		
I1	1.7	4.8
I2	0.8	5.6
I3	0.6	5.9
I4	0.8	6.9
I5	0.1	7.0
I6	0.0	6.1

Numbers followed by the same letter are not significantly different at $p<0.05$

Petiole Nitrogen and Nitrate

Total nitrogen levels in P-YFEL increased linearly with increasing nitrogen application rate at all sampling times (Figure 4). At each nitrogen rate, petiole total nitrogen levels remained constant from 43 to 78 DAE. At the first and second sampling times (43 and 57 DAE) total nitrogen levels showed a decreasing trend with increasing irrigation rate. Irrigation rate had no affect on petiole total nitrogen levels at the third sampling (78 DAE).

Petiole nitrate levels also increased significantly in response to applied nitrogen (Figure 5). However, in contrast to total nitrogen, at the first sampling time (43 DAE), petiole nitrate was depressed at the 600 kg N/ha rate. Petiole potassium levels were also depressed by the the 600 kg N/ha treatment at the early sampling (data not shown) suggesting that the toxic effects of this treatment were possibly the result of ammonia toxicity.

Unlike total nitrogen, petiole nitrate levels decreased with progressively later samplings. Irrigation rate had no affect on petiole nitrate levels at 43 and 78 DAE. At 57 DAE petiole nitrate showed a decreasing trend with increasing irrigation rate.

Figure 6 shows the relationship between petiole nitrate and total yield at each sampling time based on individual plot data from irrigation treatment 5 (I5) only. The nitrate levels associated with maximum yield were 16,000, 14,000 and 8,000 ppm at 43, 57 and 78 DAE, respectively.

Discussion

The linear relationships between irrigation rate and total and processing yields in our experiment are similar to those found by other workers. For example, Hane and Pumphrey (1984) found that the total yield of Russet Burbank potatoes (Y) was related to water use (W) by the production function:

$$Y = 0.142W - 28.7 \tag{3}$$

where Y is in t/ha and W is in millimetres and was applicable over the range 300 to 650mm. They found that the amount of water required for maximum yield was 625-650mm. Similarly, Shalhevet *et al.* (1983), working in Israel, found a linear relationship between total yield and seasonal water application for Desiree potatoes given by:

$$Y = 0.119W - 23.5 \tag{4}$$

This function was applicable over the range 300 to 850mm, and 820mm was required for maximum yield. For marketable yield, Shalhevet *et al.* found a production function of:

$$Y = 0.128W - 40 \tag{5}$$

The slopes of these production functions are very similar to those found in our experiment (0.15 - total yield, 0.179 - processing yield). However, our optimum water application level

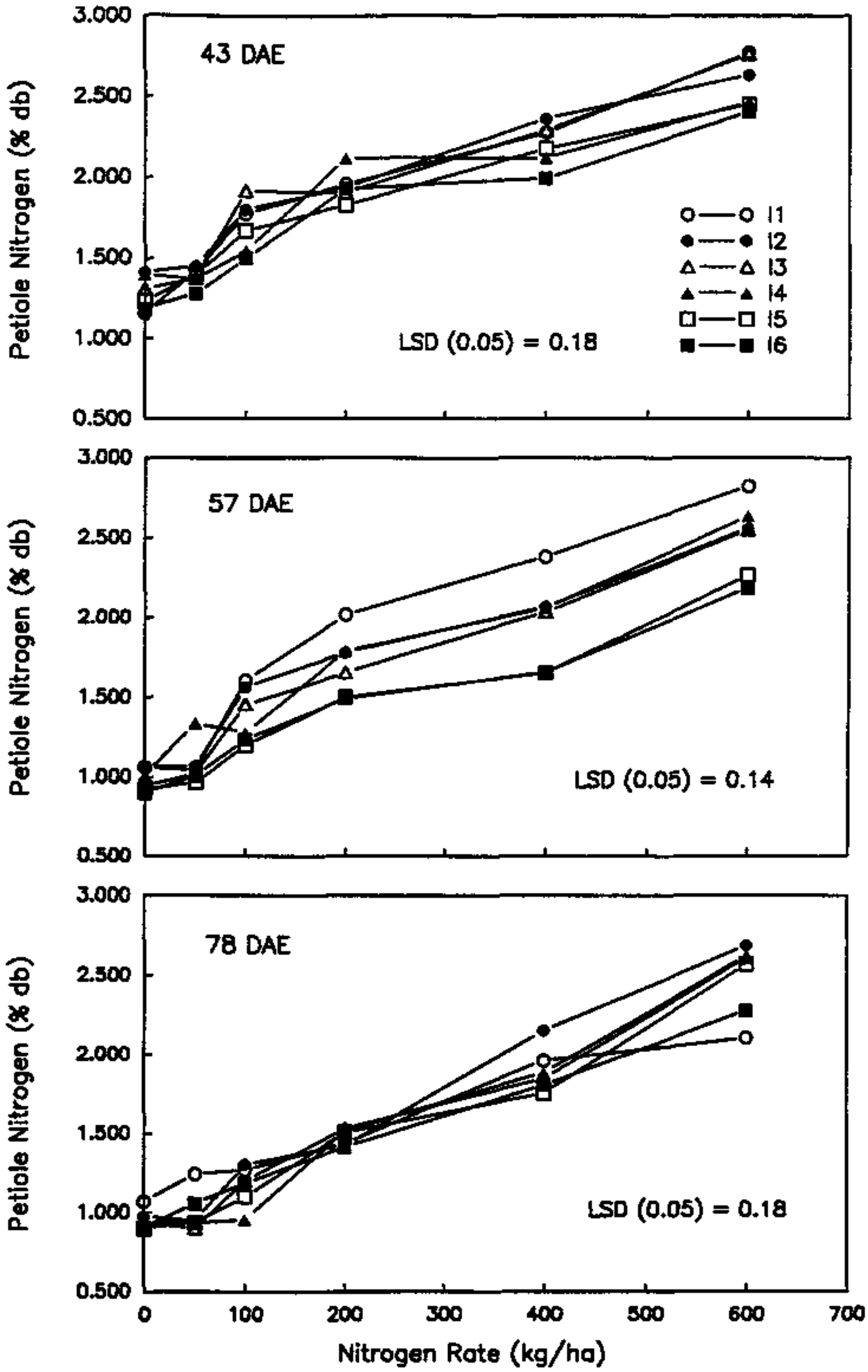


Fig. 4 **Response of petiole total nitrogen levels of nitrogen rates and irrigation treatments. LSD's are for the nitrogen main effect.**

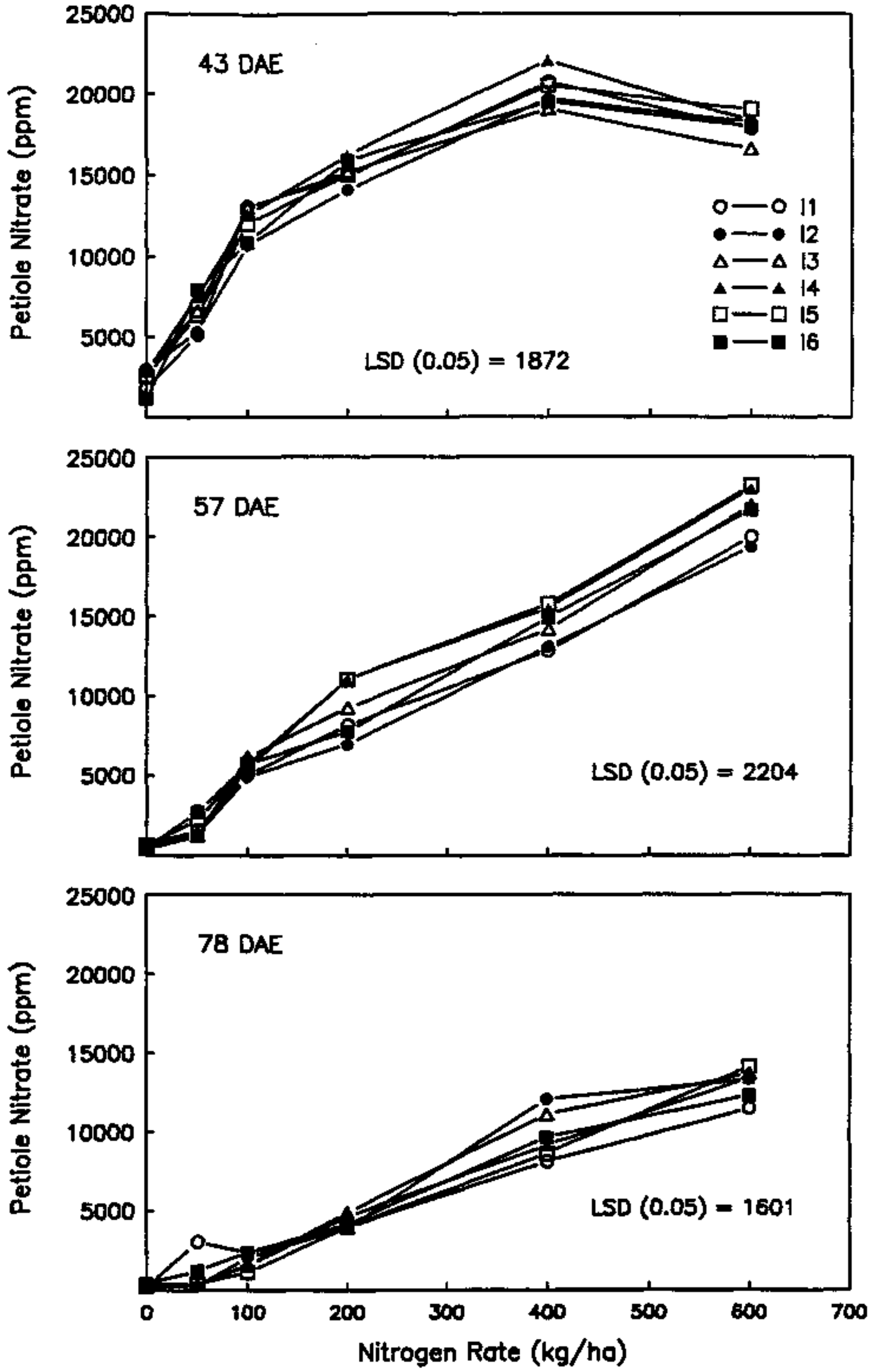


Fig. 5 **Response of petiole nitrate-nitrogen concentrations to rates of applied nitrogen and irrigation treatments. LSD's are for the nitrogen main effect.**

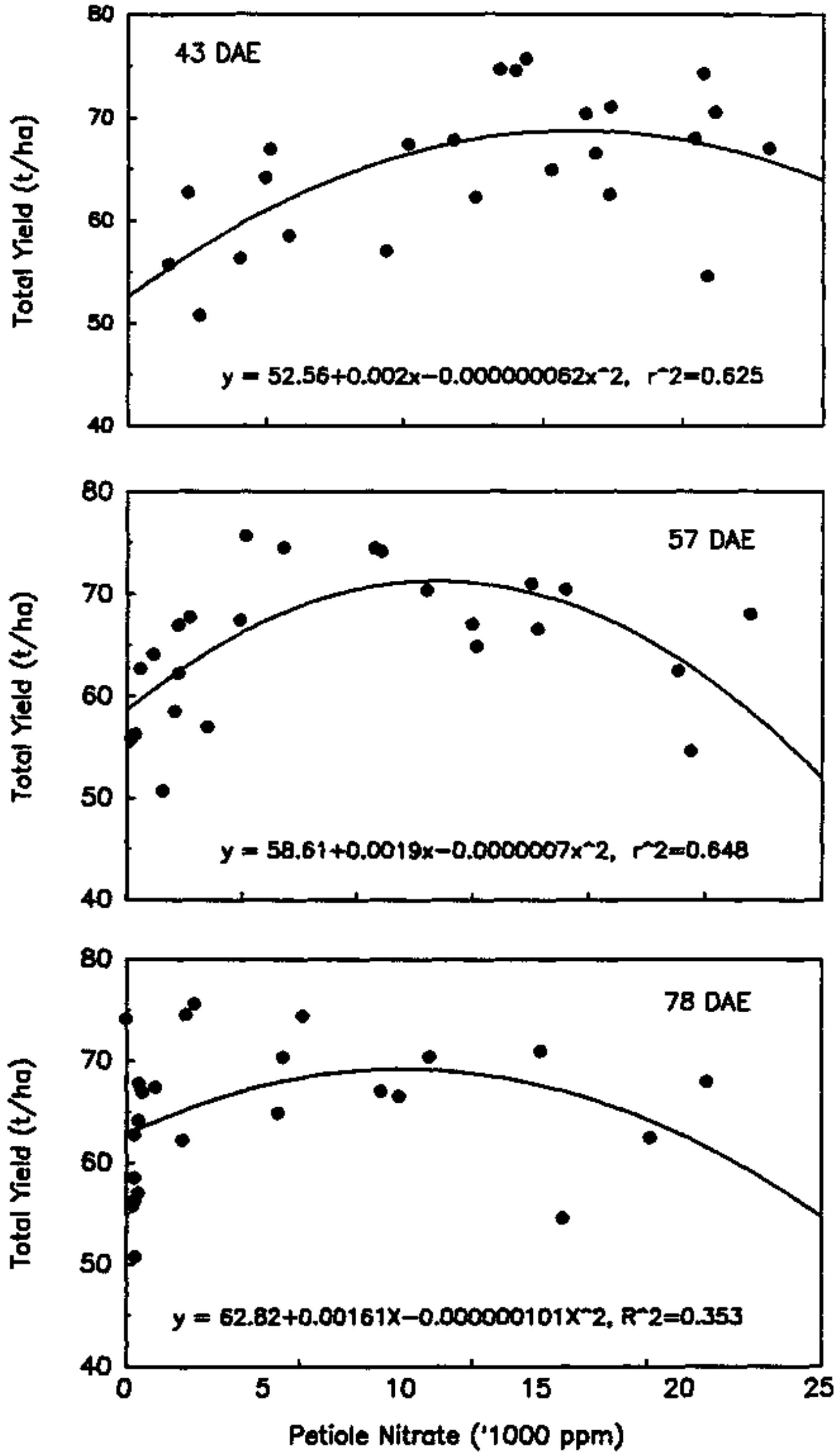


Fig. 6 **Relationships between petiole nitrate-nitrogen concentrations and total yield at three sampling times.**

was considerably lower (475mm). The differences can be explained in terms of seasonal evaporative demand and temperature conditions. In our experiment, 475mm represented 107% estimated ET or 74% Class A pan evaporation. In the work of Hane and Pumphrey (1984), 650mm corresponded with 104% calculated potential ET averaged over two seasons. Shalhevet *et al.* (1983) did not present ET data, but 820mm corresponded with 104% of Class A pan evaporation. The higher Epan replacement level required in Israel may be due to higher temperatures leading to increased evaporative losses from exposed soil. As in our experiment, these workers found that yield remained unchanged at water application levels in excess of that required for maximum yield.

Soil texture is important in determining optimum irrigation levels. Millar and Martin (1983), also using a line source sprinkler system, found that on a sandy soil the total and marketable yield of Russet Burbank potatoes increased linearly with increased irrigation up to the equivalent of 100% estimated ET. However, on a loam soil, maximum total and marketable yield was achieved at irrigation levels equivalent to 70-80% estimated ET. Wright and Stark (1990) presented data which showed that sprinkler irrigated Russet Burbank potatoes required water equivalent to 52% Class A pan evaporation on a silt loam soil in southern Idaho, US. These workers did not present any detailed soil information. The soil type studied in our experiment had a sandy surface. The work of Hane and Pumphrey (1984) and Shalhevet *et al.* (1983), quoted above, was also conducted on loamy sands. It would appear important, therefore, to clearly define the target soil type when stipulating an optimum ET or Epan replacement level.

Previous research has shown that water stress before or at the time of tuber initiation can reduce tuber numbers and subsequently lead to reduced yields (MacKerron and Jefferies, 1986; Moorby and Milthorpe, 1978). In our experiment, differential irrigation treatments were imposed at or just after tuber initiation so tuber numbers were not affected. Water stress reduced yields through reductions in individual tuber weights. Van Loon (1981) found that water stress during tuber bulking was more detrimental to tuber size and final yield than early stress. High tuber yields require long tuber bulking periods which in turn require the maintenance of a large green leaf area for extended periods (Moorby and Milthorpe, 1975; Dyson and Watson, 1971). Based on the number of days from planting to 90% foliage senescence, we found that increased water stress reduced green leaf area duration.

Tuber specific gravities were significantly higher in the driest irrigation treatment. The very low average tuber size in this treatment may partly explain the high values. The transfer of water from tubers to leaves in water stressed plants, thereby increasing the concentration of soluble solids in tubers, has also been suggested as a possible explanation (Wolfe *et al.*, 1983).

We have shown that tuber specific gravity decreases in response to increasing nitrogen up to rates sufficient for maximum yield (Fig. 3). At higher nitrogen rates, specific gravity remained unchanged. This response is in contrast to the pattern observed by Dahlenburg *et al.* (1990) at two of four sites where they found specific gravity increased with nitrogen up to rates adequate for maximum yield and then decreased with excessive nitrogen rates. The response of specific gravity is not always consistent. For example, in studies with Nooksack potatoes, Lauer (1986b) measured decreasing specific gravity with increased nitrogen rates in two of six experiments. In the remaining four experiments nitrogen rate had little effect on specific gravity.

Millar and Martin (1987) found that the proportion of tubers with malformations such as second growth, increased with increasing water stress, particularly if the stress was imposed at an early growth stage. In our experiment, irrigation rate had no effect on the proportion of tubers with second growth. As with the tuber number response, this can be explained by the fact that our differential irrigation treatments were not imposed until the time of tuber initiation. The 600 kg/ha nitrogen rate significantly increased the proportion of tubers with second growth, suggesting that the early toxic effects of this treatment have been detrimental to tuber shape.

The lack of a positive interaction for yield between irrigation and nitrogen rates suggests that nitrogen leaching was not a problem on our experiment site. The nitrogen/irrigation interaction was partly over-shadowed by the toxic combination of 600 kg N/ha and high irrigation rates. However, as shown in Figure 1, the yield response to nitrogen rates up to 400 kg/ha tended to increase as irrigation rate increased. A similar result was found by Ojala *et al.* (1990).

The total and processing yield responses to nitrogen were well described by quadratic functions. The optimum nitrogen rate suggested from these functions (335 to 375 kg N/ha) is similar to the optimum rates found by other workers (e.g. Lauer 1986a, 400-425 kg N/ha; Roberts and Cheng 1988, 336 kg N/ha).

Total and processing yields with nil nitrogen were 79 and 75% of the maximum yields, respectively. This suggests that the site had a relatively high residual soil nitrogen level. In a nitrogen response experiment conducted on a neighboring site with a lower residual soil nitrogen level (as indicated by the yield of the nil nitrogen treatment - 42% maximum yield) in the same season , an optimum nitrogen rate of 450 kg/ha was found (McKay, pers comm.). Clearly, for accurate determination of total nitrogen requirements, knowledge of the residual soil nitrogen level is required.

Petiole NO_3-N analysis at an early growth stage has been suggested as a means of over-coming the need to have detailed residual soil nitrogen data in order to determine total crop N requirements (Roberts and Cheng, 1988). Corresponding to our sampling times, these workers suggested that petiole NO_3-N levels above 11000, 9200 and 7000 ppm at 43, 57 and 78 days after emergence respectively, were adequate for maximum yield of Russet Burbank potatoes. The critical levels we suggested are higher than these and are more in line with the levels suggested by Gardner and Jones (1975) and Sharma and Arora (1987).

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APPENDIX 1 **Average tuber weights and yield components.**

* There were no treatment effects on the number of tubers per plant which averaged 10.4
* There were no treatment effects on the number of tubers per stem which averaged 3.4
* Irrigation rates had no effect on the number of stems per plant. However, nitrogen rate had a small effect on stem number per plant:

	Nitrogen Rate (kg/ha)						
	0	50	100	200	400	600	LSD (0.05)
Stems/plant	2.99	3.16	3.31	3.23	3.12	2.83	0.28

Average Tuber Weight (g)

Nitrogen Rate (kg/ha)	Irrigation Treatment I1	I2	I3	I4	I5	I6	Mean
0	96	105	145	156	163	135	133
50	105	122	148	158	163	156	142
100	108	131	150	170	176	172	151
200	115	106	162	181	193	182	157
400	110	127	169	187	178	210	164
600	113	159	160	163	174	174	157
Mean	108	125	156	169	175	171	
LSD (0.05) for nitrogen main effect							14

Average Processable Tuber Weight (g)

Nitrogen Rate (kg/ha)	Irrigation Treatment I1	I2	I3	I4	I5	I6	Mean
0	157	146	182	192	200	172	175
50	152	174	185	191	197	193	182
100	164	167	198	213	211	204	193
200	174	164	212	216	227	228	203
400	162	182	218	233	235	260	215
600	174	205	215	236	232	228	215
Mean	164	173	202	213	217	214	
LSD (0.05) for nitrogen main effect							13

APPENDIX 2 Yield of tubers in various size categories

0 99g Tuber Size Range (t/ha)

Nitrogen Rate (kg/ha)	Irrigation Treatment						Mean
	I1	I2	I3	I4	I5	I6	
0	12.3	12.2	7.4	6.3	6.1	9.0	8.9
50	10.5	10.3	7.6	7.0	6.4	5.9	7.9
100	11.1	8.4	8.9	6.2	6.1	4.8	7.6
200	11.2	11.4	6.1	5.6	6.1	6.0	7.7
400	10.6	10.1	6.3	4.9	6.6	5.0	7.3
600	9.5	7.1	6.9	7.4	6.8	6.3	7.3
Mean	10.9	9.9	7.2	6.2	6.4	6.2	
LSD (0.05) for nitrogen main effect							NS

100 - 249g Tuber Size Range (t/ha)

Nitrogen Rate (kg/ha)	Irrigation Treatment						Mean
	I1	I2	I3	I4	I5	I6	
0	17.1	21.7	32.3	33.1	30.7	34.8	28.3
50	21.3	26.5	35.2	30.2	33.8	33.5	30.1
100	21.1	27.8	32.0	33.2	31.0	37.0	30.8
200	23.2	25.1	31.7	33.5	29.7	32.0	29.2
400	25.6	28.2	25.7	27.1	31.1	25.8	27.2
600	24.0	25.7	25.9	21.3	25.2	26.4	24.7
Mean	22.0	25.8	30.4	29.7	30.8	31.6	
LSD (0.05) for nitrogen main effect							3.6

249 - 450g Tuber Size Range (t/ha)

Nitrogen Rate (kg/ha)	Irrigation Treatment						Mean
	I1	I2	I3	I4	I5	I6	
0	2.0	2.7	12.5	17.4	19.0	11.2	10.8
50	3.2	8.4	12.9	18.0	20.5	16.7	13.3
100	4.5	9.3	18.0	21.1	24.5	20.7	16.4
200	4.5	5.4	13.6	31.0	29.6	25.1	18.2
400	3.7	11.5	25.4	30.1	25.4	28.7	20.9
600	6.4	17.4	25.2	20.4	26.0	24.2	20.0
Mean	4.1	9.1	17.9	23.1	24.2	21.1	
LSD (0.05) for nitrogen main effect							4.1

>450g Tuber Size Range (t/ha)

Nitrogen Rate (kg/ha)	Irrigation Treatment I1	I2	I3	I4	I5	I6	Mean
0	0.0	0.0	0.3	0.7	0.0	0.4	0.2
50	0.0	0.0	1.3	2.3	0.7	1.9	1.0
100	0.0	0.7	0.3	2.4	2.5	2.1	1.3
200	0.3	0.3	2.7	1.3	4.3	3.4	2.1
400	0.7	0.3	4.3	6.9	5.8	12.1	5.0
600	0.9	3.0	3.3	5.2	3.3	4.8	3.4
Mean	0.3	0.7	2.0	3.1	2.8	4.1	
LSD (0.05) for nitrogen main effect							1.5

Rejects (rots and greens only) (t/ha)

Nitrogen Rate (kg/ha)	Irrigation Treatment I1	I2	I3	I4	I5	I6	Mean
0	0.1	0.3	0.0	0.5	0.6	0.5	0.3
50	0.4	0.4	0.2	1.3	0.3	0.4	0.5
100	0.5	0.3	0.5	1.1	0.9	1.4	0.8
200	0.5	1.5	0.4	1.2	1.7	1.4	1.1
400	0.4	0.7	0.6	1.2	0.9	1.4	0.9
600	0.5	0.6	2.3	5.3	2.8	3.4	2.5
Mean	0.4	0.6	0.7	1.8	1.2	1.4	
LSD (0.05) for nitrogen main effect							0.7

6.2 EFFECT OF APPLYING IRRIGATION AT DIFFERENT LEVELS OF SOIL MOISTURE POTENTIAL ON THE YIELD AND QUALITY OF RUSSET BURBANK POTATOES

(Experiment 90MC31)

Aim

This preliminary experiment was designed to test the hypothesis that to achieve maximum yield and quality of Russet Burbank potatoes, the available soil moisture level needed to be maintained above 75%.

Materials and Methods

Site details

The experiment was conducted at the Manjimup Horticultural Research Centre (34°18' S, 116°7' E). The soil was a gravelly loamy sand over mottled clay at 50-60 cm (Dy 3.11, Northcote, 1979). Some of the relevant soil physical characteristics are given in Table 1.

Table 1. Soil characteristics of experimental site[1] (n=5).

Depth (mm)	% Gravel	% Coarse Sand	% Fine Sand	% Silt	% Clay	Bulk density (g/cm^3)	Field Capacity (%v/v)	Wilting Point (%v/v)	Avail. Water Capacity (%v/v)
0-400	31.8	37.0	40.6	0.2	13.2	1.24	25.7	10.9	14.8
400-500	49.0	46.5	37.0	6.5	10.0	1.55	18.6	8.4	10.2
500-1000	29.2	29.1	39.8	7.8	24.0	1.59	25.2	12.4	12.8

1. gravel = >2mm, coarse sand = 2-0.2mm, fine sand = 0.2-0.02mm, silt = 0.02-0.002mm, clay = <0.002mm)

Experimental design and treatments

The experiment consisted of a randomised block arrangement of 3 irrigation treatments replicated 4 times. Individual plots were 7.4 m long by 6 rows wide. Row spacing was 0.8 m. Plots were separated on all sides by a 5 m buffer that was allowed to return to natural pasture after the pre-planting cultivations. The treatments were based on soil water potential (SWP) measured at a depth of 30 cm below the top of the potato ridge using automatic Irrometer® tensiometers. Throughout the entire crop growth period, sufficient water was applied at each irrigation to return the soil to field capacity when the SWP reached -18, -26, or -50 kPa. These SWPs corresponded with available soil moisture levels in the top 60 cm of the profile of 80%, 72% and 53%, respectively.

Trial establishment

Prior to the experiment the site used had been in a predominantly grass pasture for 8 years. Site preparation began 4 weeks before planting when the site was sprayed with paraquat + diquat (2 L/ha Sprayseed®). The site was cultivated 3 weeks before planting using a mould-board plough. A combination of fenamiphos (24 L/ha Nemacur 400®) and chlorpyriphos (6 L/ha Lorsban 500®), together with pre-planting fertilisers, were then incorporated with a rotary hoe. The pre-planting fertilisers consisted of 10 kg magnesium/ha ($MgSO_4.7H_2O$) and a trace element mix containing 15 kg/ha $CuSO_4$, 7.5 kg/ha ZnO, 10 kg/ha $MnSO_4$ and 15 kg/ha Borax.

Prior to planting, 3000 kg/ha of Potato Manure E® fertiliser (3.5% N, 7% P, 6.6% K) was banded in twin rows to the side of and below seed piece placement level using a single row fertiliser applicator. Ridges were formed at the same time. The experiment was planted on 5 October 1990. Fourty five to 50 gram hand-cut seed pieces, which were dusted with tolclofos-methyl (2 kg/t Rizolex®), were hand planted into the preformed ridges at an in-row spacing of 0.35 m (35,700 plants/ha). The ridges were reformed 3 weeks after planting.

Irrigation

The irrigation system was installed three weeks after planting. Individual plots were uniformly irrigated using a 3.0 m x 2.4 m arrangement of DAN 2001® (95 L/h) pressure regulated mini-sprinklers. Each sprinkler was fixed to a 1.0m stake which enabled them to be kept above the crop at all times. The water application rate was 8 mm/h. Separate electronic irrigation controllers were used to control the timing and amount of water applied to each treatment. When the average of the 4 automatic tensiometers in each treatment (one per replication) reached the desired SWP, an irrigation event was triggered. The amount of water applied to each plot was measured with raingauges which were emptied after each irrigation.

Irrigation treatments were imposed from the time of 50 % emergence (13 November 1990) and were terminated at the time of 50 % crop senescence in each treatment (~ 22 February 1991). Plants were considered to have emerged when one stem had visibly broken through the soil surface. Measurement of crop senescence was based on visual assessment of percent ground cover.

Soil moisture monitoring

In addition to the tensiometer at a depth of 30 cm, a second tensiometer was installed in each plot at 50 cm. This tensiometer provided a check on the adequacy of water applications. In addition to the electronic monitoring, which did not record tensiometers readings, readings from all tensiometer were taken daily between 8.00 and 10.00 am. The soil moisture profile was measured periodically throughout the experiment using a neutron probe which had been calibrated on site. Total volumetric soil moisture (VSM) contents were calculated by integrating readings at depths of 20, 30, 40, 50, 60, 80 and 100 cm. This data provided a second check on the adequacy of water applications. Also, consumptive water use (CWU) was estimated for each treatment from the water balance:

$$CWU = VSM \text{ at emergence} - VSM \text{ at harvest} + \text{applied irrigation} + \text{rainfall}$$

Drainage below 100 cm was assumed to be negligible. Plots of the changes in soil water potential (SWP) in each treatment are shown in Figures 1, 2 and 3. Unfortunately, due to a system malfunction, at two consecutive irrigations during the critical tuber bulking period in the -50 kPa treatment, irrigation water was applied before the target SWP was reached (i.e. at -40 kPa instead of -50 kPa). As a result, this treatment did not experience as much stress as it otherwise may have done. (Note: -40 kPa is equivalent to ~60% ASW).

Agronomic management

A total of 150 kg nitrogen/ha was applied post-emergence in 2 equal applications: 220 kg NH_4NO_3/ha on 13 November and 27 November 1991. Metribuzin (750 mL/ha Sencor 480 SC®) was applied one week after emergence for annual weed control. Preventative control of fungal leaf diseases was achieved with weekly applications of either chlorothalonil (2 L/ha Bravo®) or iprodione (2 L/ha Rovral®) which began six weeks after emergence. Permethrin (150 mL/ha Ambush®) was used to control green looper and potato tuber moth and methamidophos (700 mL/ha Nitofol®) was used for control of aphids and potato tuber moth when necessary.

Plant sampling

Whole plant samples were taken from 0.7m sections of one row of each plot on 6 occasions during the crop growth period - 54, 68, 83, 96, 110 and 124 days after planting. The samples were washed and separated into tubers, stems and leaves + petioles. The fresh weight of tubers was recorded. Tubers were then diced and all samples were dried at 70°C in a forced draught oven for 48 hours. Sample dry weights were recorded.

Harvest and grading

All plots were allowed to naturally senescence before harvest. 6 m lengths (17 plants) from three inside rows in each plot were harvested using a single row harvester on 10 March 1991. Tubers from each plot showing second growth were counted and weighed separately. Similarly, all tubers with any greening, rots or growth cracks were counted and weighed separately. The remaining tubers were counted and weighed into the following size categories: <100g, 100-250g, 250-450g and >450g. Processing grade tubers were >100g and free of any defects.

Tuber quality assessment

Twenty tubers (>250g) from each plot were sliced longitudinally and inspected for hollow heart and other internal defects. Tuber specific gravity was measured on a 3.5 kg sample of 100-450g tubers from each plot using the weight in air - weight in water method (Redshaw and Fong, 1972).

Statistical analyses

Data were analysed by analysis of variance using GENSTAT (GENSTAT 5 Committee 1987), and l.s.d.s ($P<0.05$) calculated for comparison of treatment means.

Results

Water applied

The number of irrigation events required to maintain the SWP above the preset levels decreased from 22 at -18 kPa to 8 at -50 kPa (Table 2). Similarly the total amount of irrigation water applied decreased as SWP decreased. Consumptive water use showed a similar trend. Insufficient replicate data was collected to determine whether the differences in CWU were statistically significant.

Table 2. Effect of irrigation treatments on the number of irrigation events , irrigation water applied and consumptive water use (CWU)

SWP treatment (-kPa)	Number of irrigations	Irrigation water applied (mm)*	CWU[1] (mm)
18	22	437	513
26	14	373	468
50	8	315	427

1. including 85 mm of rain

Yield and tuber quality

The irrigation treatments had no significant (P<0.05) effect on any measured yield parameters (Table 3). In all treatments, 70% of processing grade tubers were in the 100-250 g weight range, with 27% weighing between 250 and 450 g. Less than 2% of all tubers weighed more than 450 g.

The proportion of all tubers with second growth increased from 14% in the -18 kPa treatment to 18% in the -50 kPa treatment, though the treatment effect was not significant.

The specific gravity of tubers was significantly (P<0.05) higher in the -50 kPa treatment than at -18 or -26 kPa.

For all treatments, the mean number of tubers per plant was 12, and the mean number of tubers per stem was 2.3.

No hollow heart was found in any tubers. Irrigating at -50 kPa resulted in a significantly (P<0.05) higher proportion of tubers with internal brown fleck (Anon 1986), compared with irrigating at higher SWPs.

Table 3. Effect of irrigation treatments on total and process yield, yield components and tuber specific gravity.

SWP (-kPa)	Total yield (t/ha)	Process yield (t/ha)	Yield in each tuber weight category (t/ha)			
			0-100 g	100-250 g	250-450g	>450g
18	56.8	43.4	8.5	29.9	12.3	1.1
26	52.3	40.7	9.1	28.8	10.9	1.0
50	57.3	43.3	8.4	30.0	12.2	1.1
l.s.d. (0.05)	ns	ns	ns	ns	ns	ns

Table 3. Cont'

SWP (-kPa)	Rejects (t/ha)				Internal brown fleck (%)	Specific gravity
	Second growth	Green	Rots	Cracks		
18	7.9	0.6	0.05	0.05	3.0	1.08025
26	7.7	0.6	0.07	0	6.4	1.08025
50	10.5	1.0	0.13	0	8.9	1.08250
l.s.d. (0.05)	ns	ns	ns	ns	4.1	0.00150

Water use efficiency

Water use efficiency (WUE, kg total tuber yield/mm consumptive water use) increased from 111 kg/mm in the -18 kPa treatment to 134 kg/mm in the -50 kPa treatment.

Plant growth

As shown in Figures 1 - 4, there were no significant treatment effects on any of the measured plant growth components at any growth stage. Tuber dry matter percentage also increased throughout growth at the same rate in all treatments (Figure 5).

Discussion

Under the conditions in which this experiment was conducted, neither total nor processing tuber yield was reduced when the SWP was allowed to decrease to -50 kPa (i.e. 53% available soil moisture). Notwithstanding the problems experienced with the -50 kPa treatment, this result disproves our null hypothesis that yield would be reduced when ASW fell below 75%.

The reduction in the number of irrigation events and total irrigation water applied to the -50 kPa treatment, compared with irrigating at a higher SWP, represents a potential saving both in terms of labour and pumping costs. However, the significant increase in internal brown fleck caused by this treatment would likely lead to a small reduction in the dollar return per tonne of processing potatoes which may, in part, offset the irrigation cost savings.

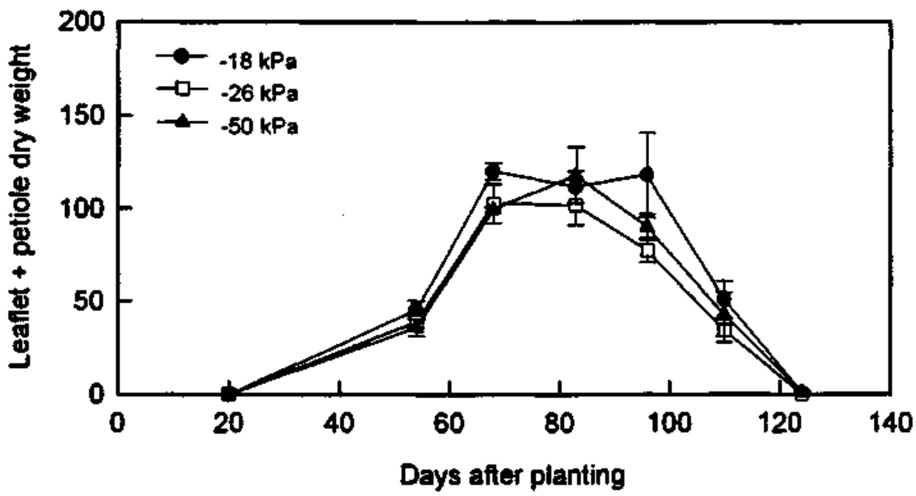

Figure 1. **Changes in leaf and petiole dry weight (g per sample) with time after planting in Russet Burbank potatoes when irrigated in response to three different soil moisture potentials. Data points are means of four replicates ± s.e.**

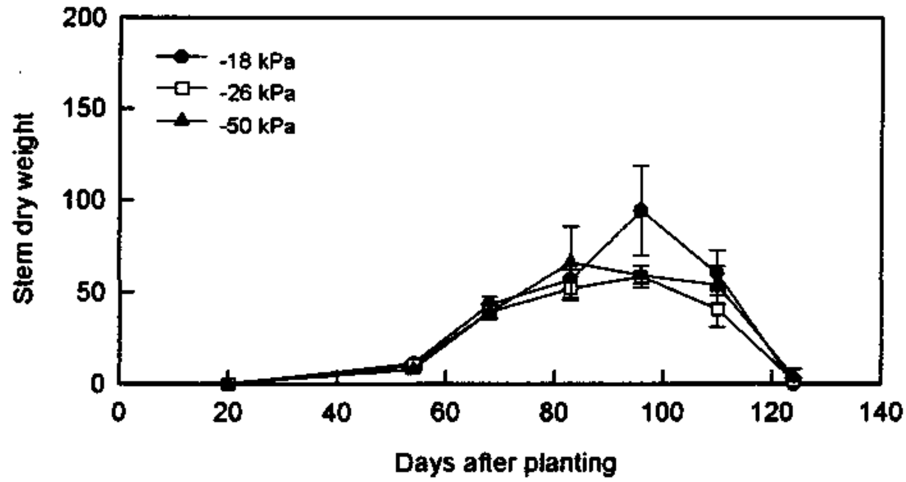

Figure 2. Changes in stem dry weight (g per sample) with time after planting in Russet Burbank potatoes when irrigated in response to three different soil moisture potentials. Data points are means of four replicates ± s.e.

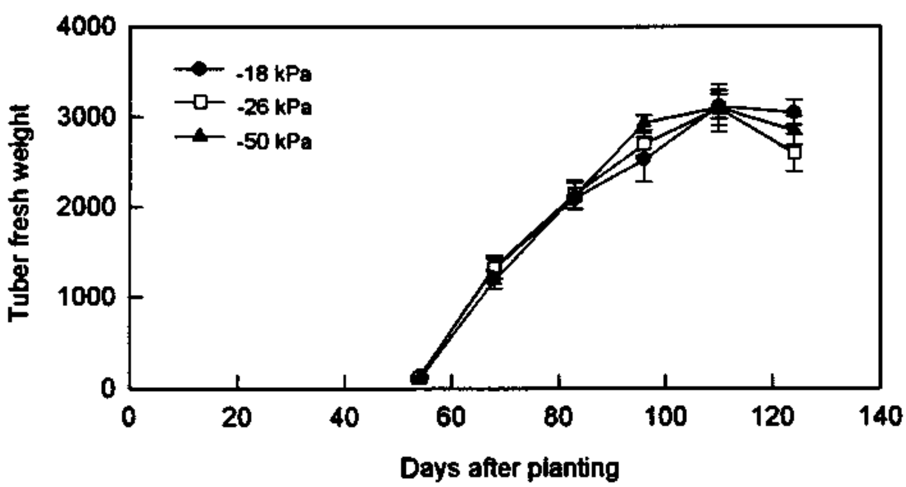

Figure 3. Changes in tuber fresh weight (g per sample) with time after planting in Russet Burbank potatoes when irrigated in response to three different soil moisture potentials. Data points are means of four replicates ± s.e.

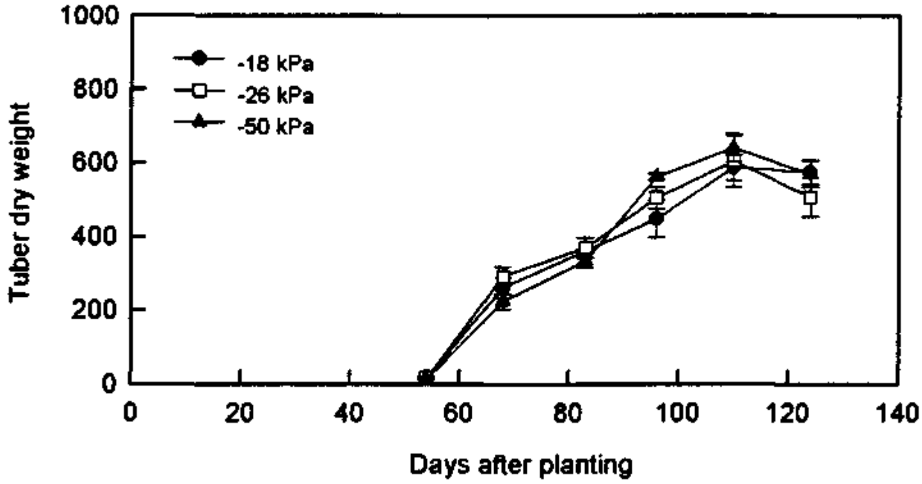

Figure 4. **Changes in tuber dry weight (g per sample) with time after planting in Russet Burbank potatoes when irrigated in response to three different soil moisture potentials. Data points are means of four replicates ± s.e.**

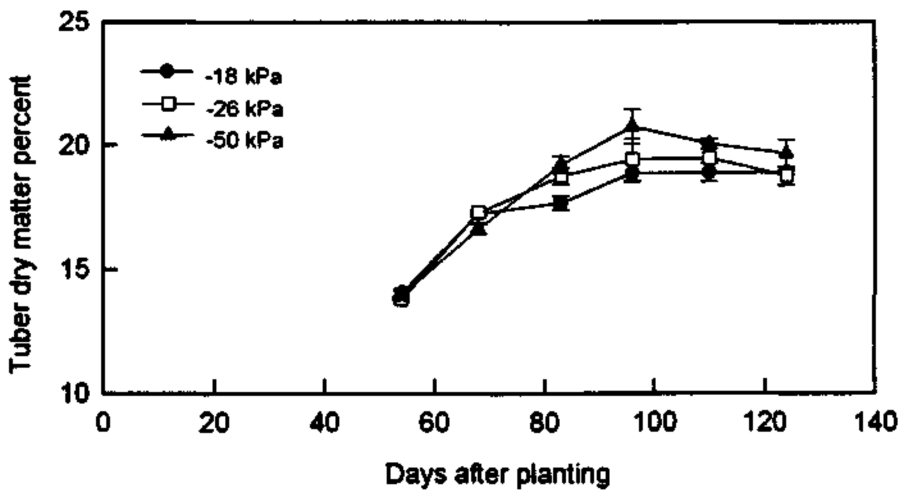

Figure 5. **Changes in tuber dry matter percentage with time after planting in Russet Burbank potatoes when irrigated in response to three different soil moisture potentials. Data points are means of four replicates ± s.e.**

When the SWP was allowed to decrease to -50 kPa between irrigations, up to 45 mm of water was required to return the soil profile to field capacity. In commercial practice, on paddocks with slopes exceeding 6%, which are common in the Manjimup-Pemberton area, such a large quantity of water applied in a single application using high impact sprinklers or high application rates may cause excessive runoff. To safely adopt such an irrigation schedule, the use of low impact sprinklers with a water application rate not exceeding 8 mm/hr may be required.

The water use efficiencies achieved in this experiment for Russet Burbank potatoes (111 to 134 kg/mm) are equivalent to those achieved in the work of Hane and Pumphrey (1984, 122 kg/ha) and of Martin *et al.* (1992, 108 kg/ha). However, Hane and Pumphrey found that maximum yield of Russet Burbank was associated with a CWU of between 625 and 650 mm. In the work of Martin *et al.*, CWU of 678 mm was required for maximum yield. Maximum total yields achieved in both these studies exceeded 75 t/ha. By comparison, in our experiment, the maximum yield was only 57 t/ha with a CWU of between 427 and 513 mm. This difference in total yield can be partly explained by the shorter crop growth period (emergence to 50% senescence) in our work (100 days) compared with that in the work of Hane and Pumphrey (116 days) and Martin *et al.* (110 days). Increasing the total amount of nitrogen above the 255 kg N/ha applied in our experiment, may help extend the crop growth period and lead to higher total yields. Further investigation is required to determine the optimum nitrogen application level for Russet Burbank potatoes grown in the Manjimup-Pemberton area, and to examine the effect that increased nitrogen application levels have on crop irrigation requirements.

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6.3 DEFINING THE OPTIMUM SOIL WATER POTENTIAL REGIME FOR MAXIMUM YIELD AND QUALITY OF 'RUSSET BURBANK' POTATOES.

(Experiments 91MC23 & 92MC22)

Summary

Field experiments were conducted in the 1991/92 and 1992/93 seasons in the lower south west of Western Australia to examine the effect of irrigating at different soil water potentials (SWP) (measured at 30 cm depth) on the yield and quality of Russet Burbank potatoes. The 1991/92 experiment consisted of four treatments which were irrigated at SWPs of -20, -35, -50 or -80 kPa throughout growth. Three similar treatments were imposed in the 1992/93 experiment with irrigation being applied at -20, -40 or -80 kPa. In the second experiment, 6 additional treatments examined the effects of irrigating at different SWPs during 3 growth stages (emergence to early tuber bulking, early bulking to late tuber bulking and late bulking to maturity - first, second and third growth stages, respectively). In both experiments, highest total and processing yields and lowest levels of tuber malformations were obtained by irrigating at a SWP of -20 kPa during all growth stages. However, in the 1992/93 experiment, allowing the SWP to decline to -40 kPa between irrigations during the second and third growth stages had no effect on yield or tuber quality. This latter regime did not result in any water saving, but reduced the total number of irrigation events from 26 to 18. Total yield was reduced by irrigating at -20, -40 and -80 kPa during the first, second and third growth stages, respectively. Both total and processing yields were reduced when irrigation was applied at -80 kPa during the second and third growth stages. Allowing the SWP to decrease to -80 kPa during the first growth stage, followed by irrigation at -20 kPa during later growth stages, had no effect on total or processing yields, but significantly increased the proportion of malformed tubers (malformed tubers were not removed from the processing grade). The proportion of tubers with second growth was not affected by irrigation treatments. In 1991/92, highest tuber specific gravity was achieved by irrigating at -35 kPa, while specific gravity was reduced by irrigating at -80 kPa. Tuber specific gravities were not significantly affected by irrigation treatments in 1992/93. Tuber yield increased linearly as consumptive water use (CWU) increased to 610 mm. Water use efficiency (kg total yield/mm CWU) was not affected by irrigation treatment and, for the highest yielding treatments, ranged between 140 and 152.

Introduction

Large scale production of French fries began in Western Australia in 1987, with the opening of a production plant at Manjimup, in the south west of the State. During the 1993/94 season, 35,000 tonnes of potatoes were processed through this plant. The preferred potato cultivar is 'Russet Burbank' due to its consistently high dry matter content and large yield potential. However, local growers have had difficulty producing high processing yields of this cultivar using traditional cultural practices.

In Western Australia, irrigation is an essential component of potato production systems. Most growers currently irrigate their crops by experience based on a calender schedule or observations of the crop and soil. Very few growers use objective methods of irrigation scheduling such proportional replacement of Class A pan evaporation or direct measurement of soil moisture. Russet Burbank is well known for its high sensitivity to moisture stress (Millar and Martin, 1987). Therefore, more objective irrigation scheduling guidelines for Russet Burbank potatoes are needed.

Tensiometers have been successfully used for irrigation scheduling in potatoes. Dubetz and Krogman (1973) compared the use of tensiometers for irrigation scheduling in potatoes with two other methods - irrigating when the crop first showed signs of moisture stress and an irrigation budget method designed to maintain at least 50% available soil moisture. They found that irrigating at a soil water potential (SWP) of -40 kPa gave significantly higher yields of Netted Gem potatoes compared with the other two methods. Jones and Johnson (1958) suggested that the best time to irrigate Sebago potatoes was when the SWP reached -30 kPa. Shimshi and Susnoshi (1985) found that the yields of five different potato cultivars was reduced when the SWP at the 30 cm depth dropped below -40 kPa. From a review of the available literature, Van Loon (1981) concluded that the optimum SWP for maximum yield was in the range between -20 kPa and -60 kPa, with the absolute optimum being dependent upon climate and plant and soil characters.

The impact of water stress on yield and quality depends on the timing and severity of the stress. Water stress during the period between planting and early tuber growth can reduce tuber numbers and yield (Slater and Goode, 1967; Jana *et al.*, 1989), increase the incidence of malformed tubers (Nichols and Ruf, 1967; van Loon, 1981) and reduce tuber cooking quality (Stark and McCann, 1992). Stress during mid tuber growth and crop maturation usually has a greater effect on yield than tuber quality (Millar and Martin, 1987; Martin *et al.*, 1992). Larsen (1984) found that to avoid yield and quality losses in Russet Burbank potatoes, the available soil water level should be maintained above 65% throughout crop growth.

Aim

The objective of the study reported here was to define the optimum soil water potential regime for Russet Burbank potatoes produced under Western Australian conditions.

Materials and methods

Site details

Two experiments were conducted at the Manjimup Horticultural Research Centre (34°18' S, 116°7' E), one in each of the 1991/92 and 1992/93 seasons. The soil was a gravelly loamy sand over mottled clay at 50-60 cm (Dy 3.11, Northcote, 1979). Some of the relevant soil physical characteristics are given in Table 1.

Experimental design and treatments

Experiment 1 (91MC23)

The first experiment (1991/92) consisted of a randomized block arrangement of 4 irrigation treatments replicated 3 times. The treatments were based on SWP measured at a depth of 30 cm below the top of the potato ridge using Irrometer® tensiometers. Throughout the entire crop growth period, sufficient water was applied at each irrigation to return the soil to field capacity when the SWP reached -20, -35, -50 or -80 kPa. These SWPs corresponded with available soil moisture levels in the top 60 cm of the profile of 78%, 64%, 53% and 40%, respectively (Fig. 1).

Table 1. **Soil characteristics of experimental site[1] (n=5).**

Depth (mm)	% Gravel	% Coarse Sand	% Fine Sand	% Silt	% Clay	Bulk density (g/cm³)	Field Capacity (%v/v)	Wilting Point (%v/v)	Avail. Water Capacity (%v/v)
0-400	31.8	37.0	40.6	0.2	13.2	1.24	25.7	10.9	14.8
400-500	49.0	46.5	37.0	6.5	10.0	1.55	18.6	8.4	10.2
500-1000	29.2	29.1	39.8	7.8	24.0	1.59	25.2	12.4	12.8

1. gravel = >2mm, coarse sand = 2-0.2mm, fine sand = 0.2-0.02mm, silt = 0.02-0.002mm, clay = <0.002mm)

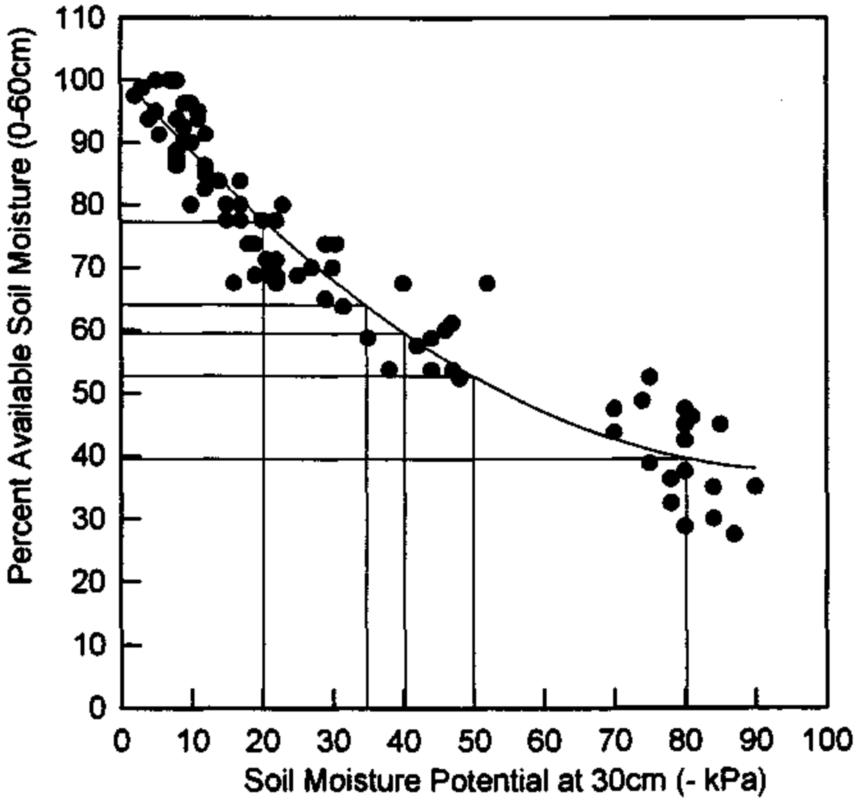

Figure 1. **Percent available soil moisture in the top 60 cm of the profile as a function of soil water potential measured at 30 cm depth.**
The equation of the fitted line is:

$$Y = 101 - 1.3X + 0.0066X^2, \quad R^2 = 0.92$$

Experiment 2 (92MC22)
The second experiment (1992/93) comprised a randomised block arrangement of nine irrigation treatments replicated four times. The treatments were based on SWP measured as in experiment 1, with irrigation being applied when the SWP reached -20 kPa, -40 kPa or -80 kPa. However, the SWPs at which irrigation events were triggered varied across three crop growth stages - planting to early tuber bulking (0 - 41 days after 50% emergence (DAE)), early tuber bulking to late bulking (42 - 81 DAE), and late tuber bulking to maturity (> 81 DAE). At 41 DAP the length of the longest tuber on plants in all treatments was between 40 and 50 mm. Details of the changes in SWP between these growth stages within each treatment are given in the tables. -40 kPa corresponded with an available soil moisture level of 60% in the top 60cm of the profile (Fig. 1).

Trial establishment
Prior to each experiment the site used had been in a grass/clover pasture for five years. Site preparation began six weeks before planting when the sites were sprayed with glyphosate (3 L/ha Roundup®). The sites were cultivated four weeks before planting using a mould-board plough. Metham sodium (500 L/ha Vapam®) (1991/92) or a combination of fenamiphos (24 L/ha Nemacur 400®) and chlorpyriphos (6 L/ha Lorsban 500®) (1992/93), together with pre-planting fertilisers, were then incorporated with a rotary hoe. In Experiment 1, the pre-planting fertilisers consisted of 100 kg nitrogen/ha (NH_4NO_3), 50 kg potassium/ha (KCl), 10 kg magnesium/ha ($MgSO_4.7H_2O$) and a trace element mix containing 15 kg/ha $CuSO_4$, 7.5 kg/ha ZnO, 10 kg/ha $MnSO_4$ and 15 kg/ha Borax. In Experiment 2, the pre-planting fertilisers consisted of 70 kg nitrogen/ha (NH_4NO_3), 85 kg potassium/ha (K_2SO_4) plus the same levels of magnesium and trace elements as in Experiment 1.

In both experiments, individual plots were 7.5 m long by 6 rows wide. Row spacing was 0.8 m. Plots were separated on all sides by a 5 m buffer that was allowed to return to natural pasture after the initial cultivation. Experiment 1 was planted on 21 October, 1991 and Experiment 2 on 16 October, 1992. 50 g hand-cut seed pieces, which were dusted with tolclofos-methyl (2 kg/t Rizolex®), were planted at an in-row spacing of 0.35 m (35,700 plants/ha) by a single row tractor mounted planter/fertiliser applicator. At the same time, 3300 kg/ha of Potato E® fertiliser (3.5% N, 7% P, 6.6% K) was banded in twin rows to the side of and below the seed pieces. All plots were machine moulded one week after planting.

Irrigation
The irrigation system was installed after final moulding. Individual plots were uniformly irrigated using a 3.0 m x 2.4 m arrangement of DAN 2001® (95 L/h) pressure regulated mini-sprinklers. Each sprinkler was fixed to a 1.0m stake which enabled them to be kept above the crop at all times. The water application rate was 10 mm/h. The amount of water applied to each plot was measured with raingauges which were emptied after each irrigation.

In each experiment, between planting and 50 % emergence, all treatments were uniformly irrigated to maintain adequate soil moisture levels. Irrigation treatments were imposed from the time of 50 % emergence and were terminated at the time of 50 % crop senescence. Plants were considered to have emerged when one stem had visibly broken through the soil surface. Measurement of crop senescence was based on visual assessment of percent ground cover.

Soil moisture monitoring
In addition to the tensiometer at a depth of 30 cm, a second tensiometer was installed in each plot at 50 - 60 cm. This tensiometer provided a check on the adequacy of water applications. All tensiometer readings were taken daily between 8.00 and 10.00 am. The soil moisture profile was measured periodically throughout each experiment using a neutron probe which had been calibrated on site. Total volumetric soil moisture (VSM) contents were calculated by integrating readings at depths of 20, 30, 40, 50, 60, 80 and 100 cm. This data provided a second check on the adequacy of water applications. Also, total consumptive water use (CWU) was estimated for each treatment from the water balance:

$$CWU = VSM \text{ at emergence} - VSM \text{ at harvest} + \text{applied irrigation} + \text{rainfall}$$

Drainage below 100 cm was assumed to be negligible, with the exception of 65 mm of rain received in a 36 hour period 2 days after first emergence in experiment 2. 26 mm of rain received during the day before this event had raised the soil water content to field capacity. Therefore, approximately 61 mm of the later rain was assumed to have drained through the profile and was not included in the calculation of CWU.

Agronomic management
In experiment 1, a total of 250 kg nitrogen/ha was applied post-emergence as follows: 297 kg NH_4NO_3/ha on 8 November 1991, 148 kg urea/ha on 29 November and 50 kg urea/ha on 23 December, 14 January 1992 and 3 February. In addition, 41.5 kg/ha of potassium (K_2SO_4) was applied on 23 December 1991. In experiment 2, a total of 245 kg nitrogen/ha and 76 kg potassium/ha was applied post-emergence as follows: 300 kg NH_4NO_3/ha on 24 November 1992, 200 kg urea/ha on 11 December, 200 kg KNO_3/ha on 24 December and 50 kg urea/ha on 12 January 1993.

Metribuzin (750 mL/ha Sencor 480 SC®) was applied two weeks after emergence for annual weed control. Preventative control of fungal leaf diseases was achieved with weekly applications of either chlorothalonil (2 L/ha Bravo®) or iprodione (2 L/ha Rovral®) which began six weeks after emergence. Permethrin (150 mL/ha Ambush®) was used to control green looper and potato tuber moth and methamidophos (700 mL/ha Nitofol®) was used for control of aphids and potato tuber moth when necessary.

Harvest and grading
All plots were allowed to naturally senescence before harvest. 6 m lengths (17 plants) from three inside rows in each plot were harvested using a single row harvester on 25 March 1992 and 22 March 1993. Tubers from each plot showing second growth were counted and weighed seperately. Similarly, all tubers with any greening or rots were counted and weighed seperately. The remaining tubers were counted and weighed into the following size categories: <100g, 100-250g, 250-450g and >450g. Processing grade tubers were >100g and free of any defects. In experiment 2, processing grade tubers were further graded according to whether thay had growth constrictions at the basal (pointed stem-ends), centre (dumb-bells) or apical (bottlenecks) regions of the tuber. The proportion (wt./wt.) of processing grade tubers falling into each of these categories was recorded.

Tuber quality assessment
Twenty tubers (>250g) from each plot were sliced longitudinally and inspected for hollow heart and other internal defects. Tuber specific gravity was measured on a 3.5 kg sample of 100-450g tubers from each plot using the weight in air - weight in water method (Redshaw and Fong, 1972). An additional sample of 10 tubers per plot were stored under ambient conditions for 2 weeks before the assessment of fry colour. For fry colour assessment, a single 13 mm French fry was cut longitudinally from the centre of the 10 tubers. These were then cooked in palm oil at 180°C for 2 minutes and 45 seconds. Immediately after cooking, fry colour was assessed using a USDA French Fry Colour Chart supplied by Edgell-Birds Eye, Manjimup. Also, the number of fries in each sample showing dark ends was recorded.

Statistical analyses
Data were analysed by analysis of variance using GENSTAT (GENSTAT 5 Committee 1987), and l.s.d.s ($P<0.05$) calculated for comparison of treatment means.

Results

Crop growth
In experiment 1, 50 % emergence was recorded 19 days after planting (DAP), while all plots were fully emerged by 25 DAP. Similarly, in experiment 2, 50 and 100 % emergence were recorded 20 and 26 DAP, respectively. In experiment 1, irrigation treatments had no effect on the time between planting and 50 % crop senescence (Table 2). Compared with irrigating at a SWP of -20 kPa, irrigating at -40 kPa or -80 kPa during all growth stages significantly ($p<0.05$) reduced the time betwen planting and 50 % senescence in experiment 2. Also, in experiment 2, the time between planting and 50 % senescence was reduced in treatments where the SWP was allowed to decrease to -80 kPa during the final crop growth stage, regardless of the SWP at which irrigation was triggered during the first two growth stages.

Irrigation and crop water use
In experiment 1, the number of irrigations and the total amount of irrigation water applied decreased as the SWP decreased (Table 2). This same trend was evident in experiment 2 for treatments in which the SWP at which irrigation was triggered remained constant during all growth stages (treatments 5, 6 & 7). In experiment 2, compared with irrigating constantly at -20 kPa, decreasing the SWP to -40 or -80 kPa during one or more growth stages caused a reduction in the number of irrigations and the total amount of water applied.

Table 2. Number of days between planting and 50% senescence, number of irrigation events, total irrigation water applied and consumptive water use (CWU) for each treatment soil water potential (SWP) regime in experiments 1 and 2.

Treatment number	SWP regime (0-41 / 42-81 / >81)	No. of days (planting to 50% senescence)	No. of irrigations	Irrigation water applied (mm)	CWU[b] (mm)
Experiment 1					
1	20/20/20	142	24	480	603
2	35/35/35	138	12	404	522
3	50/50/50	139	10	391	536
4	80/80/80	140	8	377	500
l.s.d (p<0.05)		ns			29
Experiment 2					
5	20/20/20	138	26	557	617
6	40/40/40	130	14	445	530
7	80/80/80	127	7	368	460
8	20/40/40	136	18	521	598
9	20/40/80	131	15	452	533
10	20/80/80	129	11	403	498
11	20/20/40	135	21	480	572
12	20/20/80	133	19	492	587
13	80/20/20	137	21	483	557
l.s.d (p<0.05)		4			28

a. Days after 50% emergence.

b. Includes rainfall - 77 mm in experiment 1and 84 mm in experiment 2. In experiment 2, total rainfall received between planting and 50% senescence was 146 mm, however, 61 mm was assumed to have drained below the crop root zone.

In the early stress treatment of experiment 2 (treatment 13), the targeted SWP of -80 kPa during the first growth stage was not reached until 40 DAE (i.e. the day before this treatment was reverted to being irrigated at -20 kPa for the remaining 2 growth stages). At 41 DAE, the largest tubers on plants in this treatment were around 40 mm long. Therefore, severe stress in this treatment occurred after the time of tuber initiation.

In both experiments, where the SWP at which irrigation was triggered remained the same during all growth stages, consumptive water use (CWU) tended to decrease as SWP decreased (Table 2). In experiment 1, irrigating at -20 kPa throughout growth resulted in significantly ($p<0.05$) higher CWU compared with irrigating at a lower SWP. Similarly, in experiment 2, irrigating at -20 kPa during all growth stages resulted in significantly ($p<0.05$) higher CWU than in all other treatments, with the exception of treatment 8, which was irrigated at -20 kPa between planting and early tuber growth and then at -40 kPa between early tuber growth and crop maturity.

Yield

For treatments irrigated at the same SWP during all growth stages, irrigating at -20 kPa (treatment 1 & 5) produced the highest total and processing tuber yields in both experiments (Tables 3). In experiment 1, tuber yields were reduced when the SWP was reduced to -35 or -50 kPa, although the total and processing tuber yields at -50 kPa were not significantly different from those produced at -20 kPa. Irrigating at -80 kPa throughout growth significantly ($p<0.05$) reduced total and process tuber yields in both experiments. These yield reductions were the result of reductions in both average tuber weight and/or tuber number per plant. Tuber numbers were not reduced in the early stress treatment in experiment 2 (treatment 13).

Table 3. Total tuber yield, process tuber yield (tubers >100 g), mean tuber weight for total tuber yield and process tuber yield, total tuber number per plant, percentage of total tubers with second growth, tuber specific gravity, and water use efficiency (WUE, kg total tuber yield/mm consumptive water use). Soil water potential (SWP) regimes as in Table 2.

Treatment number	SWP regime	Yield (t/ha) Total	Yield (t/ha) Process	Mean tuber (wt. Total	Mean tuber (wt. Process	Tuber no. / plant	Specific gravity	WUE
Exp. 1								
1	20/20/20	91.4	78.7	197	230	13.1	1.076	152
2	35/35/35	79.6	67.8	197	230	11.4	1.079	152
3	50/50/50	81.1	70.2	195	231	11.7	1.077	151
4	80/80/80	71.5	60.5	178	210	11.3	1.072	147
l.s.d ($p<0.05$)		11.7	9.5	ns	15	1.1	0.002	ns
Exp. 2								
5	20/20/20	86.1	73.2	234	289	9.8	1.082	126
6	40/40/40	73.4	57.1	215	261	9.2	1.083	129
7	80/80/80	65.5	52.7	197	247	8.8	1.078	136
8	20/40/40	84.4	71.6	221	274	10.4	1.084	127
9	20/40/80	72.1	62.4	197	250	9.5	1.082	124
10	20/80/80	70.7	61.3	197	248	9.5	1.081	135
11	20/20/40	82.4	72.8	217	259	10.1	1.084	127
12	20/20/80	78.6	67.9	218	268	9.6	1.087	122
13	80/20/20	78.7	63.3	219	278	9.7	1.082	128
l.s.d ($p<0.05$)		10.8	11.9	22	18	ns	ns	28

In experiment 2, irrigating at -20 kPa during the first growth stage and then at -40 kPa thereafter (treatment 8), produced the same total and processing tuber yield as treatment 5 (Table 3). When the SWP was further decreased to -80 kPa during the third growth stage (treatment 9), or when irrigation was triggered at -80 kPa during both the second and third growth stages (treatment 10), total yield was significantly ($p<0.05$) reduced due to a reduction in average tuber weight. Processing tuber yield in treatments 9 and 10 was also reduced compared to treatments 5 and 8, but not significantly.

Irrigating at -20 kPa for the first two growth stages and then at -40 or -80 kPa during the last growth stage (treatments 11 and 12) had no affect on total or processing tuber yield. Irrigating at -80 kPa during the first growth stage and then at -20 kPa thereafter (treatment 13) also had not affect on yield.

Within each experiment, relative tuber yields were calculated by dividing the mean total tuber yield for each treatment by the maximum mean total tuber yield. After combining the data from both experiments, we found that relative tuber yield increased linearly with increased CWU (Fig. 2). Given the high correlation between relative tuber yield and CWU, it is not surprising that water use efficiency was not affected by irrigation treatment in either experiment (Table 3).

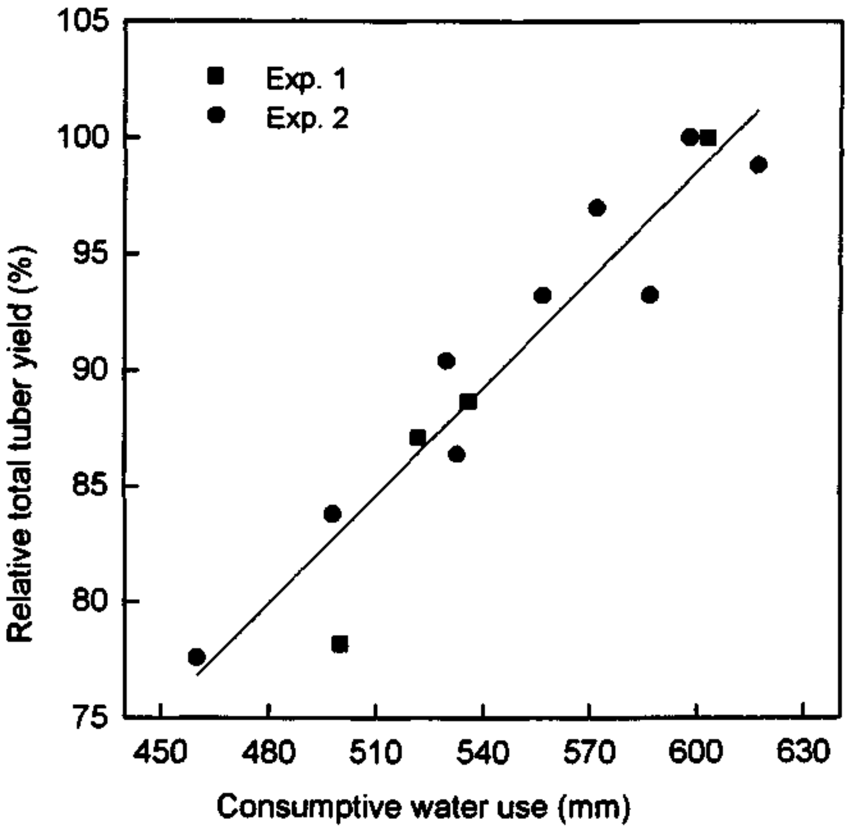

Figure 2. **The relation of relative total tuber yield (Y) to consumptive water use (W). Combined data from both experiments. The equation of the fitted line is:**

$$Y = 5.52 + 0.155W, \quad R^2 = 0.91$$

Tuber quality

In experiment 1, irrigating at -35 kPa resulted in significantly ($p<0.05$) higher tuber specific gravity compared with other treatments (Tables 3 and 4). Irrigating at -80 kPa during all growth stages resulted in reduced tuber specific gravity in both experiments, though this effect was not significant in experiment 2. Decreasing the SWP to -80 kPa during the final growth stage, after irrigating at -20 kPa during the first two growth stages (treatment 12), tended to increase tuber specific gravity, though not significantly.

Table 4. Percentage of processing tubers with pointed stem-end, dumb-bell or bottleneck shape. Data from experiment 2 only.

Treatment number	SWP regime	Pointed stem-ends	Dumb-bells	Bottlenecks
5	20/20/20	0.70	1.9	3.5
6	40/40/40	1.95	8.1	7.9
7	80/80/80	3.35	14.8	14.8
8	20/40/40	0.61	3.3	4.8
9	20/40/80	1.93	4.7	6.7
10	20/80/80	1.24	4.0	6.4
11	20/20/40	0.96	1.7	2.7
12	20/20/80	1.62	4.0	7.5
13	80/20/20	4.68	23.6	5.7
l.s.d (p<0.05)		2.60	10.8	5.7

The proportion of total yield comprised of tubers with second growth was not affected by irrigation treatment in experiment 1 and averaged 4.5% (data not shown). Very few knobby tubers were produced in any of the treatments in experiment 2, so they were not separated from general rejects.

In experiment 2, compared with irrigating at -20 kPa (treatment 5), irrigating at -80 kPa (treatment 7) during all growth stages resulted in a significant ($p<0.05$) increase in the proportion of tubers with constrictions in all tuber regions (Table 5). Early stress (treatment 13) significantly ($p<0.05$) increased the proportion of tubers with constrictions at the basal and central regions. Despite these large differences in the levels of tuber malformations, there were no treatment effects on fry colour or the percentage of 'dark ends' (data not shown). All fries, including those from different tuber shape categories, had acceptable colour.

No tubers were found with hollow heart. However, in experiment 2, a small proportion of the tubers assessed from each treatment had brown centre (~ 5%), which is a precursor to hollow heart. There were no significant treatment effects on the proportion of tubers with brown centre.

Discussion

The highest total and marketable yields and lowest level of tuber malformations were achieved by irrigating at a SWP of -20 kPa during all growth stages. By irrigating at -20 kPa, the available soil moisture (ASM) level in the top 60 cm of the profile was maintained above 77 %. This agrees well with the results of Martin *et al.* (1992) who achieved maximum yield of Russet Burbank potatoes when the ASM in the top 70 cm of a silt loam soil was maintained above 80 %. Larsen (1984) suggested that maintaining ASM above 65 % throughout all growth stages was sufficient for maximum yield and quality of Russet Burbank potatoes. However, in Larsen's work, only the top 20-25 cm of the profile was considered.

Wright and Stark (1990) presented data which suggested that the total ASM within a 50cm profile could be decreased as rooting depth increased during potato crop growth. Treatment 8 (experiment 2) confirmed this result. We found that after irrigating at -20 kPa between emergence and early tuber growth, the SWP could be decreased to -40 kPa (ASM reduced from 77 to 61%) between early tuber growth and crop maturity without affecting tuber yield or quality. Compared to irrigating constantly at -20 kPa, the latter regime, while not resulting in any water saving, would simplify irrigation management for growers by reducing the required irrigation frequency.

If Russet Burbank potatoes are to be irrigated at a SWP of -40 kPa between early tuber growth and crop maturity, to avoid a yield reduction, it would appear to be important to maintain a higher SWP during the period between emergence and early tuber growth. When irrigation was triggered at -35 or -40 kPa during all growth stages, we found that both total and processing tuber yields were reduced. Water stress between emergence and early tuber growth has been shown to reduce root growth and leaf area development (Rab and Willatt, 1987). In our work, it is possible that scheduling irrigations at -35 or -40 kPa during this early growth stage caused sufficient moisture stress to reduce early root growth and leaf area. The crop may have then been unable to compensate for this early growth restriction when irrigation continued to be scheduled at these SWPs during later growth stages. In contrast, allowing the SWP to decrease to -80 kPa between emergence and early tuber growth, then irrigating at -20 kPa thereafter had no effect on final tuber yields. It is likely that early root and leaf growth was restricted in this treatment also. However, it would appear that any growth reduction caused by the early stress was not sufficient to reduce crop growth during the second and third growth stages when high SWPs were maintained. It is possible that some compensatory growth occurred in this treatment after the early stress was relieved. Krug and Wiese (1972) (cited by Van Loon 1981) showed that, compared to continuously high available soil moisture (ASM) levels, low ASM levels (30%) during the first 24 days after emergence, followed by high ASM levels (>80%) initially decreased leaf area, but later increased foliage weight, suggesting that some compensatory growth had occurred.

Previous studies have shown that water stress during early tuber bulking leads to increased percentages of malformed tubers (Robins and Domingo, 1956; Painter and Augustine, 1976). We found the same effect here in experiment 2 where the SWP in treatments 7 and 13 was allowed to decrease to -80 kPa during early tuber growth (tubers < 50 mm). The studies by Robins and Domingo, and Painter and Augustin, also support our finding that the percentage of tubers with malformations can be increased even if the early stress does not affect final tuber yield (treatment 13). We did not remove pointed stem-end, dumb-bell or bottleneck tubers from the processing yield category because Western Australian processors accept these tubers without penalty, provided they produce fries with acceptable colour. If Russet Burbank was marketed as a fresh potato in Western Australia the high proportion of malformations caused by early water stress would reduce saleable yields.

Despite the significant increase in the proportion of pointed stem-end and dumb-bell shaped tubers caused by allowing the SWP to decrease to -80 kPa during early tuber growth, stem-end fry colour was not affected. Variable effects of early water stress on fry colour have been reported. Iritani and Weller (1973) concluded that water stress during early tuber growth leads to an increased proportion of tubers that produce French fries with dark stem-ends. In contrast, Shock *et al.* (1992) found that the percentage of tubers that produce fries with dark stem-ends is reduced by water stress before and during tuber initiation. In our work, it is possible that the stress imposed in the early stress treatments was either not sufficiently intense or was not sustained for long enough to affect stem-end fry colour. In the work of Shock *et al.*, compared with frequently irrigated treatments, a soil water potential of < -60 kPa had to be maintained for a period of 20 days around the time of tuber initiation before a significant effect on fry colour was observed. In treatments 7 and 13 in our work, a soil water potential of < -60 kPa was never maintained for longer than 7 days.

Chung *et al.* (1988) and Martin *et al.* (1992) have found that second growth in Russet Burbank potatoes is not directly affected by irrigation management. The fact that the percentage of tubers with second growth was not affected by irrigation treatments in our work confirms their findings.

Smith (1975) suggested that tuber specific gravity could be increased by reducing irrigation late in the season. Our attempt to achieve this effect in experiment 2 failed. Allowing the SWP to decrease to -40 or -80 kPa between irrigations from 81 days after emergence until crop maturity (treatments 11 and 12), despite a slight upward trend at -80 kPa, had no significant effect on tuber specific gravity. While allowing the SWP to decrease below -80 kPa during this late growth stage may have resulted in a significant increase in specific gravity, final tuber yield may have been reduced. Given that commercially acceptable specific gravities (i.e. > 1.075) were achieved in all treatments in experiment 2, continued irrigation at a SWP above -40 kPa late in the season is suggested as the most appropriate strategy to ensure maximum yields and acceptable tuber quality.

Under the conditions in which these experiments were conducted, the relationship between relative tuber yield and consumptive water use (Fig. 2) suggests that maximum yield of Russet Burbank potatoes requires a consumptive water use of approximately 610 mm. Similar water use requirements for Russet Burbank have been reported elsewhere. For example, Hane and Pumphrey (1984) found that maximum yield of Russet Burbank grown in the Columbia Basin, Oregon, was associated with a consumptive water use of 625 to 650 mm. In New Zealand, maximum yield of Russet Burbank potatoes was associated with a consumptive water use of 678 mm (Martin *et al.* 1992). In contrast, due to higher tuber yields, the water use efficiencies of the highest yielding treatments in our work (140-152 kg tuber yield/mm) were higher than in the work of Hane and Pumphrey (122 kg/mm) or of Martin *et al.* (108 kg/mm). In a temperate climate, assuming an achievable yield of 100 t/ha, Burton (1989) suggested that a water use efficiency of approximately 180 kg/mm could be achieved, while in a hot, arid climate this would be reduced to around 120 kg/mm. Our results are consistent with the fact that the prevailing mild Mediterranean climate in the lower south west of Western Australia is medial between the temperate and arid climates discussed by Burton.

Conclusions

Maximum yield of Russet Burbank potatoes is associated with total consumptive water use of around 610 mm. Irrigating at a SWP of -20 kPa during all growth stages will ensure maximum yields and tuber quality of Russet Burbank potatoes. However, after the start of tuber growth, irrigation frequency can be reduced by allowing the SWP to decrease to -40 kPa between irrigations without affecting yield or tuber quality. Allowing the SWP to decrease to -80 kPa at the start of tuber growth will increase the proportion of malformed tubers.

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7.0 IMPACT OF POTATO TUBER GROWTH AROUND ACCESS TUBES ON SOIL WATER MEASUREMENT BY NEUTRON PROBE

M.A. Hegney and H.P. Hoffmann

Summary

Neutron probes have been widely used for water use studies and irrigation scheduling in potato crops. At about the time this project started, a commercial irrigation scheduling service based on the use of a neutron probe was initiated in the Manjimup-Pemberton area. The fact that potato tubers can contain more than 80% water and that they would develop in close proximity to any neutron probe access tubes installed in the potato ridge begged the question of whether their presence would affect estimations of soil water content made using a neutron probe.

The neutron method of measuring soil water content is based on the slowing-down by water of fast neutrons emitted by a radioactive source. The actual measurement is made by lowering a probe consisting of the radioactive source and a slow neutron detector to the required depth in a suitable access hole in the ground. Soil water content is calculated from the count rate of the slow neutrons and a calibration curve. Fast neutrons emitted from the probe are just as likely to be slowed-down by water contained in potato tubers within close proximity to access tubes as by water in soil pores.

The results reported here are from experiments designed to measure the possible effect of potato tuber growth on the estimates of soil water content by a neutron probe.

Major results

- Estimates of soil water content at 20 cm depth in the potato ridge by a neutron probe were found to be significantly affected by the presence of potato tubers. The neutron probe over-estimated the soil water content when potato tubers were present. The degree of over-estimation increased as tuber growth (fresh weight per length of row) increased and as the soil dried out. Under relatively dry soil conditions (ie. soil water potential of -65 kPa), as tuber fresh weight approached 1400 g per 30cm length of row, the over-estimation of soil water content by the neutron probe at 20 cm depth approached 9mm. At a soil water potential of -15 kPa, as tuber fresh weight approached 1400 g per 30cm length of row, the over-estimation of soil water content by the neutron probe at 20 cm depth approached 5mm. These are highly significant errors when considered in relation to the optimum total soil moisture depletions limits of 15 to 25 mm for some potato varieties.
- Estimates of soil water content by neutron probe at 30cm depth were not significantly affected by the presence of potato tubers in the ridge. Most tuber development occurred above this depth

Recommendations

If a neutron probe is used for irrigation scheduling in potato crops, estimates of soil water content at 20cm depth should be corrected according to the fresh weight of tubers per unit length of row. Alternatively, gravimetric measurements of soil water content should be made at depths less than 30cm, or tensiometers should be used in conjunction with, or in place of a neutron probe for irrigation scheduling.

7.1 IMPACT OF POTATO TUBER GROWTH AROUND ACCESS TUBES ON SOIL WATER MEASUREMENT BY NEUTRON PROBE *(Experiments 90MC26 & 91MC25)*

Introduction

Neutron probes have been widely used for water use studies and irrigation scheduling in crops of potato (Solanum tuberosum)(Shalhevet *et al.* 1983; Wolfe *et al.* 1983; MacKerron and Jeffereies 1985; Rab and Willatt 1987; Marshall and Gowers 1987). Access tubes are usually located between plants in the middle of planted ridges which have a flat top and are between 10 and 20 cm high. Due to inaccuracies caused by neutron loss close to the soil surface, measurements of soil moisture with the neutron probe generally begin at a depth of 20 cm below the top of the ridge. However, potato tubers develop mostly within the ridge and well within the zone of influence of neutron probe measurements at the 20 cm depth. The high water content of the tubers may moderate neutrons, resulting in an over-estimation of the soil water content at this depth, particularly in dry soil.

Two previous studies have examined the impact of potato water content on neutron probe measurements of soil water content. MacKerron and Jefferies (1987) in a laboratory study, developed correlations between neutron count ratios and volumetric soil water content, both within and between potato ridges, at depths of 10, 20, 30 and 40 cm. They concluded that there was no significant effect of tubers on soil water estimated by the neutron probe at any of these depths. In contrast, Foroud *et al.* (1993), in a field study, measured neutron count ratios and soil water contents within and between potato ridges throughout the normal growth of a crop. At the 20 cm depth, they found that the neutron count ratios within potato ridges were significantly higher than the neutron count ratios between the ridges, while the gravimetrically measured soil water contents tended to be lower in the ridges than between them. This suggested that the tubers did have an effect on the estimation of soil water content by the neutron probe at 20 cm depth. At 45 cm, the effect was inconsistent and at 75 cm there was no effect. As stated by Foroud *et al.*, their study provided qualitative confirmation of the impact of potato tubers on neutron probe estimates of soil water content. However, if neutron probes are to be use to accurately measure soil water content in potato crops, relationships need to be developed which would allow neutron probe measurements to be corrected to take account of the water content of tubers around access tubes.

Aim

The study reported here was conducted in the field to confirm the impact of potato tubers on the soil water content estimated by a neutron probe and to develop a possible means of quantifying the effect. We took a different approach to the studies by MacKerron and Jefferies (1987) and Foroud *et al.* (1993). We made the assumption that, while the water in potato tubers may affect the soil water content estimated by a neutron probe, it would have no effect on estimates of soil moisture tension made using tensiometers. Therefore, we tested the hypothesis that the relationship between volumetric soil moisture, measured by the neutron probe, and soil moisture tension, measured using tensiometers, would remain unchanged during the growth of a potato crop.

Materials and Methods

Site details

The study comprised 2 experiments conducted between November 1990 and April 1992 on the Manjimup Horticultural Research Centre (34°18' S, 116°7' E). The soil was a loamy sand (84.7% sand, 10% gravel, 10% clay) with a bulk density of 1.35 (se ±0.065) g/cm^3.

Experimental design and treatments

The experiments involved potatoes in 1990/91 and potatoes and millet in 1991/92. Hand cut seed pieces of potato cultivar Delaware were planted 12-15 cm deep and 15 cm apart into 20 cm high ridges (basal width: 50-60 cm; dorsal width: 25-35 cm), 80 cm apart, on November 1, 1990 and December 26, 1991. The total potato plot area in both years was 60 m^2 (6 rows, each 12.5 m long). On December 26, 1991, millet was hand seeded, 2 cm deep, on the top of ridges with the same proportions as for potatoes. The area of the millet plot was 30 m^2 (6 rows, each 6.25 m long)

Aluminium access tubes, 1 m long, 50 mm external diameter and 3 mm wall thickness, were installed in all plots shortly after emergence, when individual plants could be clearly identified. The tubes were placed in the middle of the ridges. Six replicate access tubes were installed in the potato plots in both years, and 4 tubes in the millet plot in 1991/92. At the same time, tensiometers (Loktronic®, Irricrop Technologies Pty. Ltd., Narrabri, NSW, Australia) were placed in the top of the ridges at 20 cm distance from the access tubes and at 20 cm depth in 1990/91 and at 20 and 30 cm depth in 1991/92, for the determination of soil moisture tension (SMT) in centibars (cb).

Neutron probe (Model 503DR Hydroprobe, Campbell Pacific Nuclear, Pacheco, California, USA) and tensiometer readings were taken simultaneously during 4 drying cycles in 1990/91 and 3 drying cycles in 1991/92, where all crops were initially irrigated to field capacity and then allowed to dry out over a one to two week period.

Crop management

All potato crop husbandry details were as described in experiments 90MC33 and 91MC21.

Except during the drying cycles, the crops were irrigated with 20 mm of water whenever the tensiometer reading at 20 cm depth was 20 cb, using overhead sprinkler systems. In 1991/92, the potato and millet plots were irrigated simultaneously.

The millet was cut down to 10-15 cm height on 2 occasions during the 1991/92 growing season, with the excess vegetative material being removed from the plot.

Tuber sampling

Potato tuber samples were taken from a sampling row in the potato plots at 43, 63, 76, 90 and 119 days after planting (DAP) in 1990/91 and at 33, 47, 64, 78 and 106 DAP in 1991/92. On each sampling date two replicate samples were taken by inserting two metal sheets into the ridges 30 cm apart and perpendicular to the direction of the ridges. Each sample site was separated from a previous site by at least two plants. All tuber material, including parts of tubers that had been cut and were on the sampling side of the metal sheets were dug by hand. The tuber samples were washed, surface dried and weighed for fresh weight determination. The samples were then diced and dried in a forced draught oven at 70°C. Tuber dry weight was recorded after weight loss ceased.

Data analysis
Neutron count ratios (reading in soil/mean reading in water) were transformed into volumetric soil moisture (VSM) measurements using the following calibration equations - 20 cm depth, $Y = -5.848+135.36X$; 30 cm depth, $Y = 2.114+59.31X$. These calibration equations had been determined previously in unplanted ridges. Previous water balance studies had shown best agreement between applied and measured irrigation water using these equations (unpublished data).

For each drying cycle; a linear function was fitted to the relationship between VSM and lnSMT at each depth. To enable visual determination of differences between the relationships for each drying cycle, 95% confidence intervals were also plotted.

Quadratic equations were fitted to the relationship between time (days) after planting and tuber fresh weight.

Results and Discussion

Previous potato irrigation studies have shown that, for maximum yield of potatoes in the Manjimup-Pemberton area, the SMT should be maintained between 15 and 60 cb (see previous studies in this report). Therefore, it is within this approximate SMT range that any effect of tubers on estimates of VSM by the neutron probe will be most critical.

As shown in Figure 1, the relationship between VSM and SMT, at depths of both 20 and 30 cm, remained unchanged during the growth of a millet crop. This suggests that the growth of millet roots around access tubes, which was visually very dense at 20 cm depth, has not had any effect on estimates of soil moisture content by the neutron probe.

For potatoes, at the 30 cm depth, the relationship between VSM and SMT also remained unchanged during crop growth (Figure 2).

In contrast, in both of the experiments reported here, at 20 cm depth, the relationship between VSM and SMT changed during the growth of the potato crop (Figures 3 & 4). As crop growth proceeded, for a given SMT, the corresponding estimate of VSM increased. In both years, the increase in VSM at a given SMT increased as the soil dried out (i.e. SMT increased). This latter effect was more marked in 1991/92.

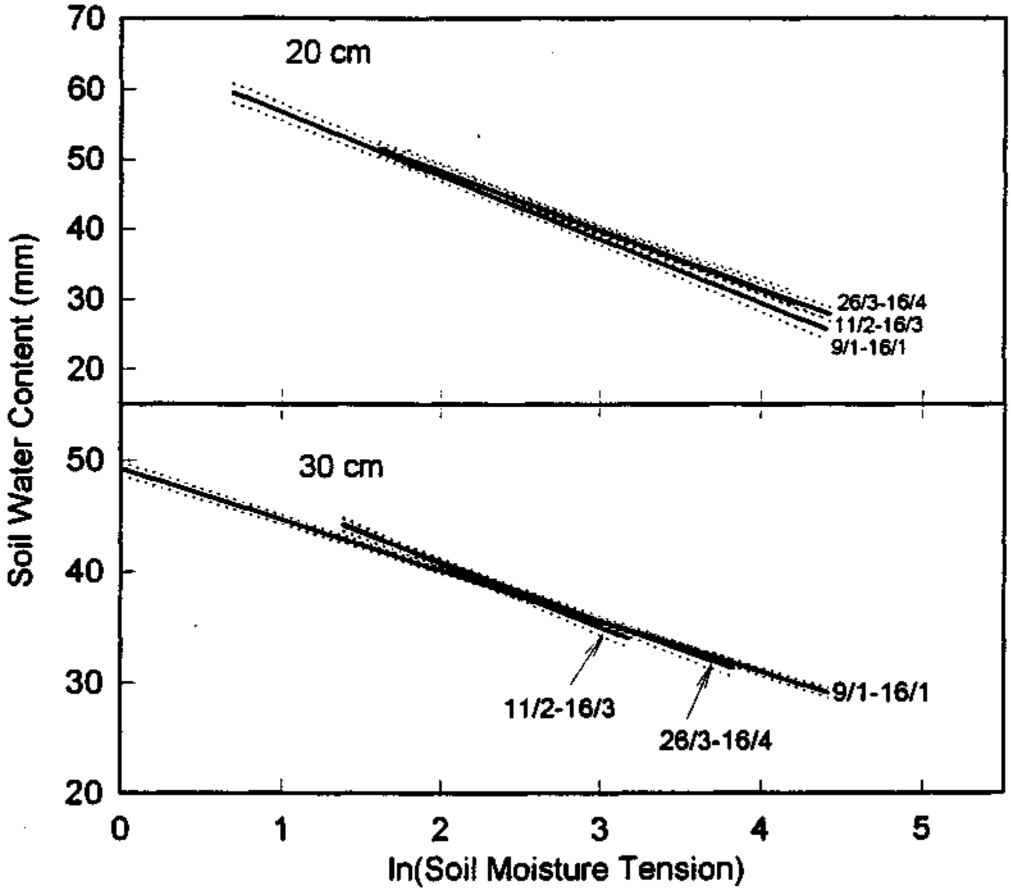

Figure 1. **Relationship between soil water content estimated by neutron probe and the natural logarithm of soil moisture tension, during three drying periods, at 20 and 30 cm depth in a 20 cm high ridge planted with millet. For each drying period, fitted regression lines (solid) are shown together with the 95% confidence intervals (dotted). The equations of the fitted lines are:**

20 cm depth	**9/1-16/1**	**SWC = 65.79 - 9.090 ln(SMT), R2=0.97 (n=28)**
	11/2-16/3	**SWC = 65.11 - 8.421 ln(SMT), R2=0.92 (n=52)**
	26/3-16/4	**SWC = 65.49 - 8.579 ln(SMT), R2=0.85 (n=48)**
30 cm depth	**9/1-16/1**	**SWC = 49.23 - 4.557 ln(SMT), R^2=0.96 (n=28)**
	11/2-16/3	**SWC = 52.21 - 5.729 ln(SMT), R^2=0.85 (n=52)**
	26/3-16/4	**SWC = 51.38 - 5.251 ln(SMT), R^2=0.90 (n=48)**

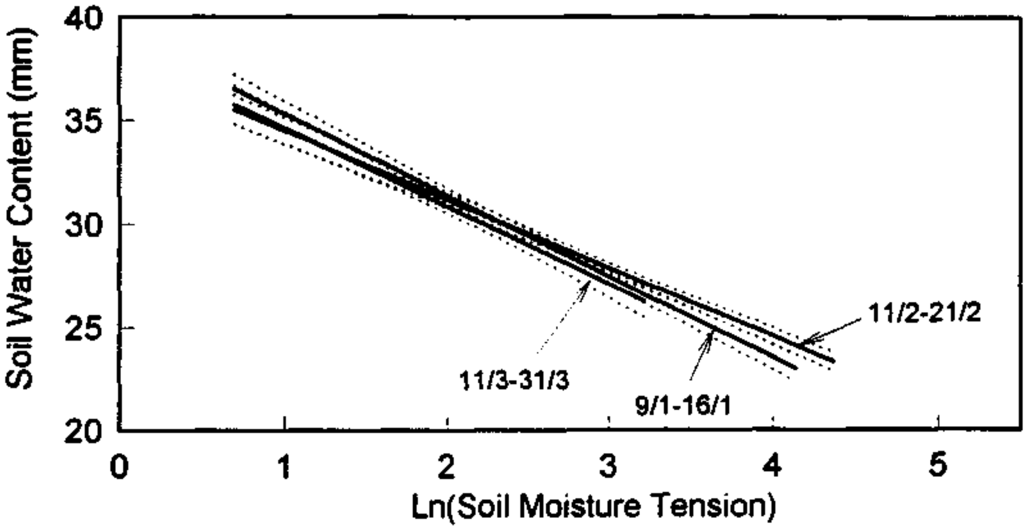

Figure 2. Relationship between soil water content estimated by neutron probe and the natural logarithm of soil moisture tension, during three drying periods, at 30 cm depth in a 20 cm high ridge planted with potatoes. For each drying period, fitted regression lines (solid) are shown together with the 95% confidence intervals (dotted). The equations of the fitted lines are:

9/1-16/1	SWC = 39.22 - 3.922 ln(SMT), R^2=0.93 (n=42)
11/2-21/2	SWC = 37.81 - 3.308 ln(SMT), R^2=0.91 (n=66)
11/3-31/3	SWC = 38.37 - 3.755 ln(SMT), R^2=0.68 (n=72)

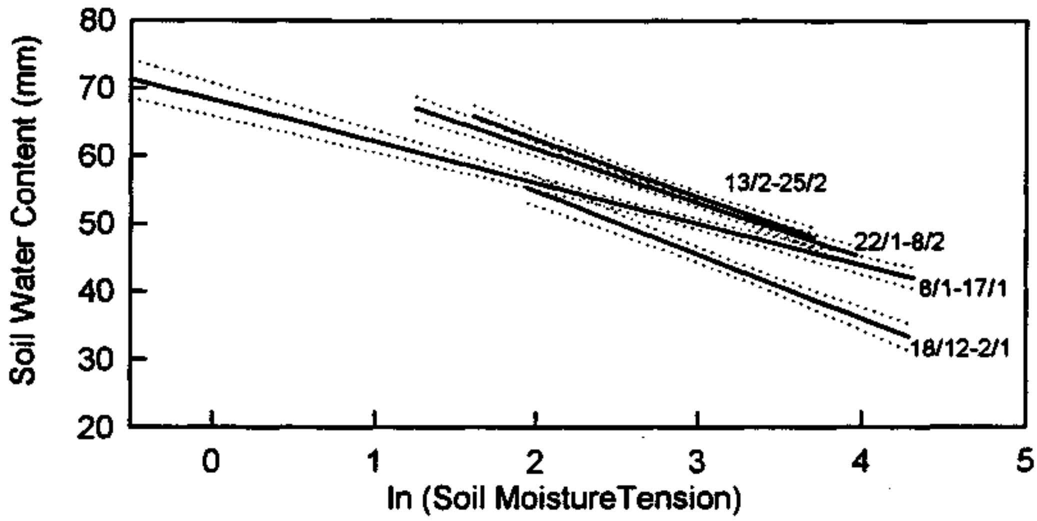

Figure 3. Relationship between soil water content estimated by neutron probe and the natural logarithm of soil moisture tension, during three drying periods, at 20 cm depth in a 20 cm high ridge planted with potatoes in the 1990/91 season. For each drying period, fitted regression lines (solid) are shown together with the 95% confidence intervals (dotted). The equations of the fitted lines are:

18/12-2/1	SWC = 73.81 - 9.437 ln(SMT), R^2=0.80 (n=37)
8/1-17/1	SWC = 68.30 - 6.096 ln(SMT), R^2=0.84 (n=41)
22/1-8/2	SWC = 77.11 - 7.995 ln(SMT), R^2=0.80 (n=59)
13/2-25/2	SWC = 79.58 - 8.516 ln(SMT), R^2=0.84 (n=38)

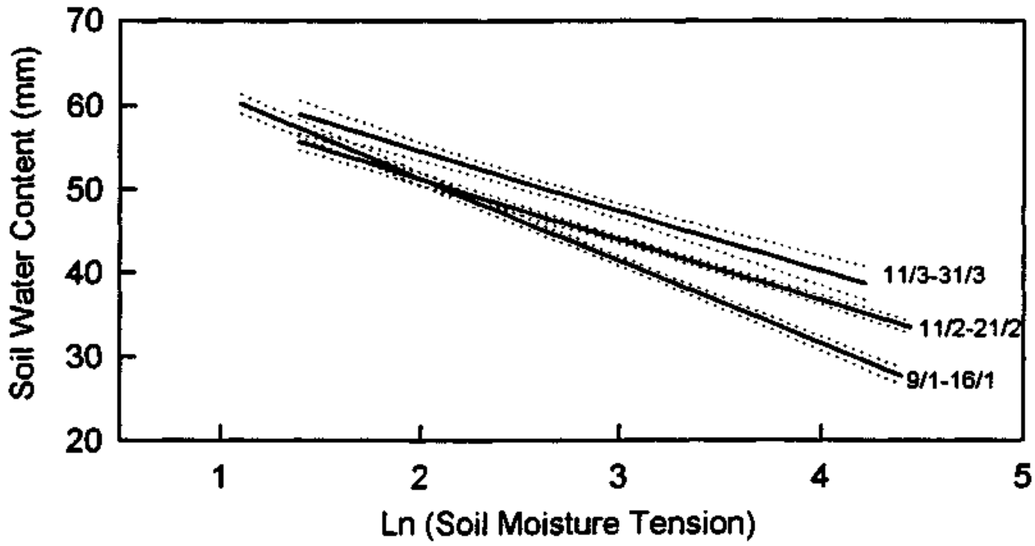

Figure 4. Relationship between soil water content estimated by neutron probe and the natural logarithm of soil moisture tension, during three drying periods, at 20 cm depth in a 20 cm high ridge planted with potatoes in the 1991/92 season. For each drying period, fitted regression lines (solid) are shown together with the 95% confidence intervals (dotted). The equations of the fitted lines are:

9/1-16/1	**SWC = 39.22 - 3.922 ln(SMT), R^2=0.93 (n=42)**
11/2-21/2	**SWC = 37.81 - 3.308 ln(SMT), R^2=0.91 (n=66)**
11/3-31/3	**SWC = 38.37 - 3.755 ln(SMT), R^2=0.68 (n=72)**

These data support the results of Foroud *et al.* (1993) who concluded from field studies that the presence of potato tubers in the ridge did impact on the estimation of VSM at 20 cm depth, but not at 45 or 75 cm depth.

From the relationships in Figures 3 and 4, and using the first drying cycle as a base line, the over-estimation (excess) of VSM at each successive drying cycle was determined at SMTs of 15 and 65 cb. As shown in Figures 5 and 6, the degree of over-estimation of VSM by the neutron probe increased as tuber growth increased. At a SMT of 15 cb, by 80 days after planting, the neutron probe was over-estimating the VSM at 20 cm depth by approximately 5 mm in both years. At a SMT of 65 cb, at 80 days after planting, the over-estimation of VSM was between 8.7 and 9.2 mm.

Over-estimation of VSM by between 5 and 9 mm would have a significant effect on irrigation scheduling in potatoes grown in the Manjimup-Pemberton area. Previous studies in this area have shown that the maximum allowable soil moisture depletion level, above which crop yield or quality is reduced, is typically between 20 and 35 mm. Over-estimating

VSM by between 5 and 9 mm (i.e. 14 and 45% of these allowable soil moisture depletion levels) could result in significant crop stress. Our results suggest that measurements of soil moisture content in a potato crop at 20 cm depth, using a neutron probe, for the purpose irrigation scheduling, must be corrected to take account of the water content in surrounding tubers.

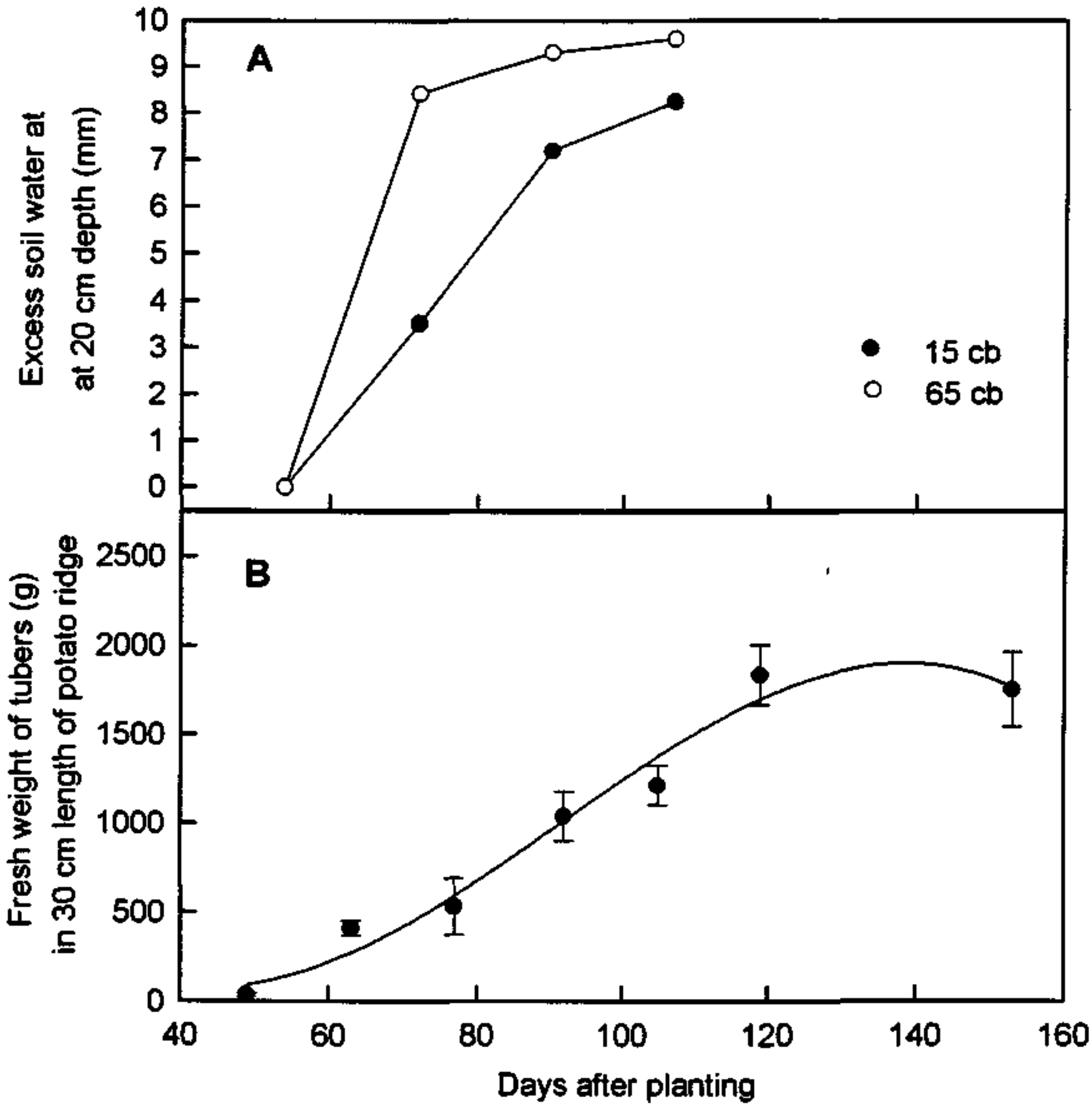

Figure 5. Relationship between time after planting and (A) excess soil water estimated by the neutron probe at 20 cm depth calculated at 15 and 65 cb, and (B) fresh weight of tubers in a 30 cm length of ridge - 1990/91. For tuber fresh weight data, vertical bars are ± s.e. and the equation of the fitted line is:

$$Y = 1604.15 - 77.78X - 1.168X^2 - 0.0043X^3, \quad R^2 = 0.81$$

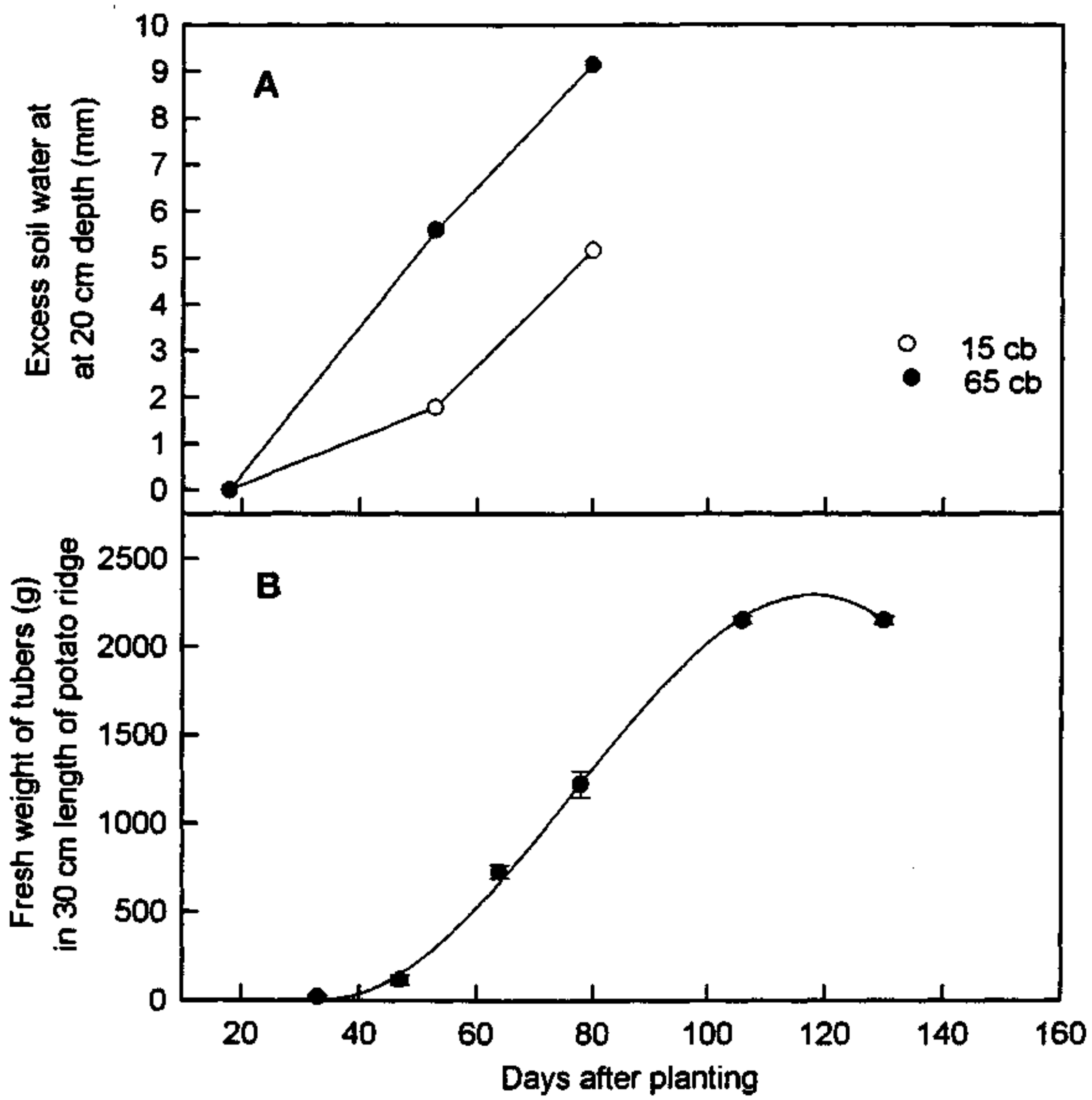

Figure 6. Relationship between time after planting and (A) excess soil water estimated by the neutron probe at 20 cm depth calculated at 15 and 65 cb, and (B) fresh weight of tubers in a 30 cm length of ridge - 1991/92. For tuber fresh weight data, vertical bars are ± s.e. and the equation of the fitted line is:

$$Y = 1436.99 - 93.052X - 1.760\ X^2 - 0.00771\ X^3,\ R^2 = 0.99$$

Given the apparent relationship between the degree of over-estimation of VSM and the fresh weight of tubers, it may be possible to correct VSM estimates made using a neutron probe by taking account of the weight of tubers present. By extrapolation of the data in

Figures 4 and 5 and combining the data from both years, relationships were established between the total fresh weight of tubers in a 30 cm length of ridge and the over-estimation of VSM (Figure 7). While the data set is limited, at a SMT of 65 cb, the relationship suggests that the amount by which VSM is over-estimated reaches a maximum at a tuber fresh weight of approximately 1400 g/30 cm. Further data is required to refine this relationship between tuber weight and over-estimation of VSM by the neutron probe.

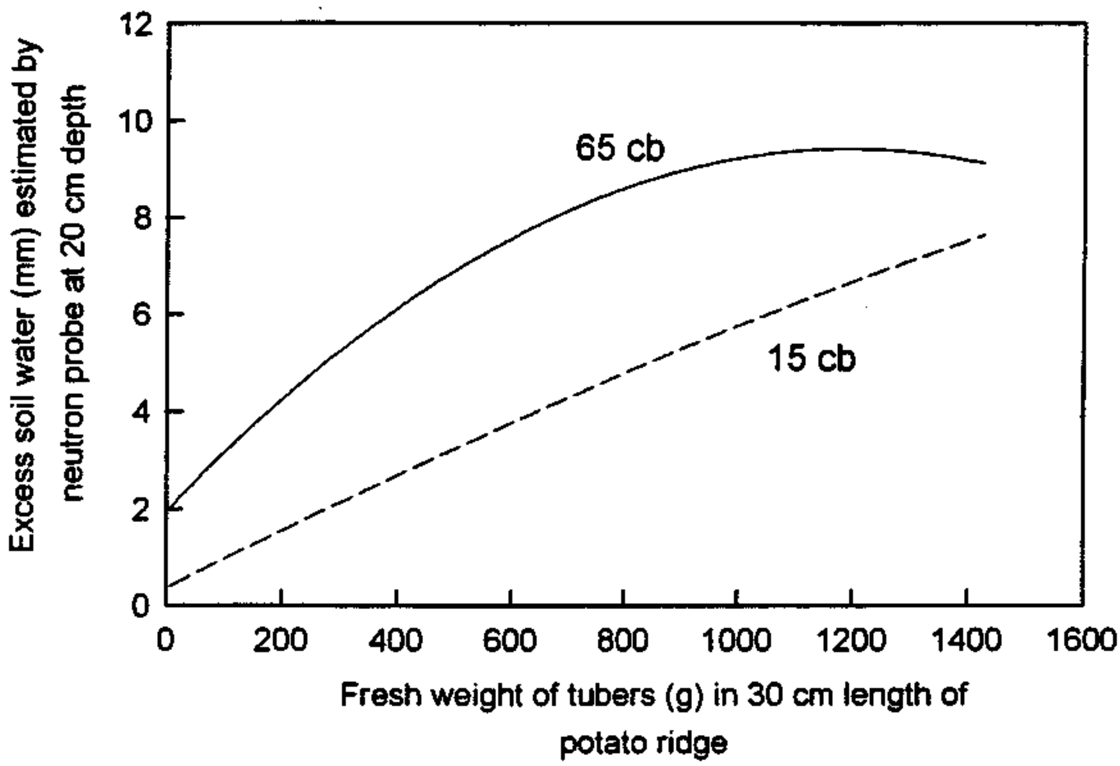

Figure 7. Relationship between fresh weight of tuber in a 30 cm length of potato ridge and the excess soil water estimated by a neutron at 20 cm depth at soil moisture tensions of 15 and 65 cb. The equations of the fitted lines are:

15 cb $Y = 0.37 + 0.0061X - 0.00000071X^2$, R^2=0.84

65 cb $Y = 1.97 + 0.0125X - 0.0000525X^2$, R^2=0.83

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