Project title:	CARROTS: The control of common scab with irrigation
Report:	Final report (December 1998)
Project number:	FV 195
Project leader:	Simon Groves ADAS Gleadthorpe Research Centre Meden Vale Mansfield Notts NG20 9PF
Location:	ADAS Gleadthorpe
Project co-ordinator:	Mr P Knights
Date of commencement:	April 1997
Date of completion:	December 1998
Key words:	Carrots, common scab, irrigation.

CONTENTS

PRACTICAL SECTION FOR GROWERS

Common scab is, as one might expect from its name, a common problem for carrot growers. It is caused by the organism *Streptomyces scabies* which can be found in most arable soils and is also known to cause scab in potatoes. Previous research has shown that *Streptomyces scabies* is less common in wet soils and that effective control of the disease in potatoes can be achieved by the timely application of irrigation. Previous research on the control of carrot scab took place at ADAS Gleadthorpe in the late 1980's and more recently in Denmark. At Gleadthorpe in a series of yield response experiments over a number of years carrot scab was controlled by irrigation in a single season. The work in Denmark published after the start of this study in 1997 recorded control of scab from irrigation applied at the 1-3 true leaf stage.

The experiments conducted at ADAS Gleadthorpe in 1997 and 1998 were designed to investigate the effect of irrigation and irrigation timing on common scab control with the aim of developing a commercial irrigation strategy for growers.

In order to maximise the chance of disease development, the experiments were conducted on a light loamy sand site using the scab susceptible variety Narbonne. Automatic rain shelters were used to exclude rainfall from the crop for four three week periods in 1997 (0-3 weeks after sowing, 3-6 weeks, 6-9 weeks and 9-12 weeks) and four four week periods in 1998 (0-4 weeks after emergence, 4-8 weeks, 8-12 weeks and 12-16 weeks). Additionally, in 1997, three sub-treatments of nil, full and sub-optimal irrigation were applied during each drought period. The rain shelters protected plots from rainfall by automatically moving over designated plots as soon as an electrical sensor detected rain. When rainfall stopped the shelters moved back thus ensuring that the micro climate remained largely unaffected.

A glasshouse experiment was conducted in 1998 to study the effects of irrigation frequency on disease development. No disease was recorded in this study.

Both the 1997 and 1998 seasons were predominantly wet with relatively low rates of evapotranspiration. But for the use of the rain shelters it would not have been possible to study the effects of drought on disease development.

The moisture content of the soil close to the root was recorded in both seasons. The computer program 'Irriguide' was used to monitor Soil Moisture Deficits (SMDs) in the whole rooting zone.

In both seasons irrigation significantly reduced the incidence of common scab. In the 1997 experiment there was no effect of irrigation timing but the lowest incidence of disease was associated with the most intensive irrigation programme.

1997

	Irrigated throughout	Sub-optimally irrigated during shelter periods	Unirrigated during shelter periods
% roots affected	12.8	14.3	19.8

In the 1998 season the absence of irrigation during the 8-12 week period after emergence was associated with increased disease.

1998

	Droughted weeks 0-4, fully irrigated at other times	Droughted weeks 4-8, fully irrigated at other times	Droughted weeks 8-12, fully irrigated at other times	Droughted weeks 12-16, fully irrigated at other times
% roots affected	5.5	9.3	26.3	6.5

These data confirm that irrigation provides a method by which carrot common scab can be controlled. However, in the development of a commercial schedule for grower, agronomic consideration and other research evidence must be reviewed.

Apart from the work reported here, there has been only one other published research study conducted on carrot common scab control. This study, conducted in Denmark (Sorenson *et al.*, 1997), reported increased disease where drought was imposed during the 1-3 true leaf stage. This contrasts with work reported here, where the 8-12 week period after emergence was associated with higher disease incidence.

Only the study at Gleadthorpe monitored the soil moisture conditions during the drought periods. In 1998 the drought period which produced the greatest incidence of scab (8-12 week period) was also associated with the highest SMDs. It is therefore possible that disease incidence was affected by drought severity and drought timing. Nevertheless, these studies have identified that the period up to 12 weeks after emergence presents the greatest risk of disease infection.

In the light of the results reported here, and the SMDs recorded in the experiments at Gleadthorpe, the following schedule is proposed.

- Irrigate to maintain the SMD below 15mm until 8 weeks after emergence

Then

- Irrigate to maintain the SMD below 30mm between weeks 8 and 12

Then

- Irrigate to maintain the SMD below 40mm until harvest

Clearly this is an intensive schedule which will present many growers with logistical problems. The greatest challenge will be to maintain SMDs below 15mm whilst ensuring metalaxyl applied to control cavity spot is not leached from the upper soil layers. The minimum practical application rate for the majority of irrigation equipment is 10mm. To achieve good control of common scab it is recommended that 10mm is applied whenever the SMD reaches 15mm during the first 8 weeks of growth. If cavity spot is not an issue, then up to 15mm may be applied during this period. After the 8 week stage the application rate can be safely increased to 25mm to keep the SMD below 30 or 40mm.

Irrigation in excess of this schedule may reduce the levels of scab further. However, this may be at the expense of other quality, pest or disease problems.

As with all pest and disease problems, varietal susceptibility to a particular problem should influence variety choice. It is known that some varieties are more resistant to common scab than other.

INTRODUCTION

It has been documented from research work conducted at ADAS Gleadthorpe that the incidence of common scab in potatoes can be reduced by the appropriate management of soil moisture (Lapwood, *et al.*, 1973). Irrigation is now widely used to control the disease in potatoes by the application of water during the first 6 weeks after tuber initiation (Bailey, 1990). The causal organism of carrot scab is similar to that of potatoes (*Streptomyces scabies*) and may also be controlled by irrigation. Published work from ADAS Gleadthorpe and Denmark has established a relationship between watering regime and the incidence of carrot scab (Groves & Bailey, 1994; Sorensen *et al.*, 1997). The results of this work suggest that low levels of soil moisture at particular times of the season may be crucial to the development of the disease.

The work described here seeks to build on this earlier work with the aim of developing a disease control strategy which identifies the period of plant growth most sensitive to disease development and describing the conditions associated with disease infection.

The commercial objective of this work is to devise an irrigation strategy for the control of carrot common scab.

OBJECTIVES

1. To determine if there is a crop growth stage particularly associated with disease infection.

2. To determine the soil moisture conditions associated with infection.

3. To develop a commercial irrigation schedule for disease control.

MATERIALS AND METHODS

Field Experiment 1998

This study was primarily designed to identify growth periods sensitive to disease infection.

The experiment was sited at ADAS Gleadthorpe on a loamy sand soil (Cuckney Series) with a low water holding capacity. The scab susceptible variety Narbonne was sown into small plots situated under an automatic rain shelter facility. These shelters protected the plots from rainfall by automatically moving over designated plots as soon as an electronic sensor detected rainfall. When rainfall stopped the shelters moved back thus ensuring that the crop micro climate remained largely unaffected.

At drilling the soil was close to field capacity in all plots. Seeds were sown using a Singulaire drill set with 4 drill units, each fitted with a 3 line coulter, to produce 4 multirows per 1.72m bed. Appropriate fertilisers and pesticides were applied (appendix 1). Irrigation and drought treatments were imposed immediately after emergence (Table 1).

Table 1 Drought treatments

1. Droughted for 4 weeks immediately after emergence but fully irrigated at all other times (11/6 - 9/7)

2. Droughted from the end of week 4 until the end of week 8 after emergence but fully irrigated at all other times (9/7 - 6/8)

3. Droughted from the end of week 8 to the end of week 12 after emergence but fully irrigated at all other times (6/8 - 3/9)

4. Droughted from the end of week 12 to the end of week 16 after emergence but fully irrigated at all other times (3/9 - 1/10)

Full irrigation was applied during periods when the plots were not sheltered.

Full irrigation was designed to maintain the soil close to field capacity i.e. a soil moisture deficit (SMD) less than 15mm early in the season and less than 25mm after the 7 true leaf stage. The computer program 'Irriguide' was used to schedule irrigation.

The moisture status of the soil surface (top 6cm) immediately adjacent to the tap root was measured using a frequency domain reflectance technique ('Theta Probe') at the end of each drought period. Soil moisture deficits of the whole rooting zone were monitored by 'Irriguide'.

All plots were harvested by hand, tops removed and the total yield and root number from each plot was recorded. A sub-sample of 100 roots was taken from each plot, washed and assessed for common scab, cracking and fanging. Common scab was assessed into four categories using the NIAB key for cavity spot; (1) nil; (2) <1.5% surface area affected; (3) 1.5% to 3% surface area affected; (4) more than 3% surface area affected. These data were used to calculate the mean percentage surface area affected.

The percentage roots affected by fanging and cracking were recorded. All data were subjected to analysis of variance using the Genstat 5 program.

Glasshouse Experiment 1998

This study was designed to investigate the possibility that the frequency of irrigation applications influences disease development.

Sufficient loamy sand soil was taken from the field site to fill 30 large plant pots. Seeds were sown into each pot before the pots were arranged in a randomised design (6 replicates of each treatment) in an unheated glasshouse. On germination, seedlings were thinned out to 4 in each pot before the watering treatments were imposed (Table 2).

Table 2 Watering Treatments

1. Watered to saturation every 2 days
2. Watered to saturation every 4 days
3. Watered to saturation every 6 days
4. Watered to saturation every 8 days
5. Watered to saturation every 10 days

Soil water content was measured using a Theta Probe in each pot at monthly intervals just before water was applied to each treatment. After 16 weeks each pot was emptied, roots washed and the incidence and relative position of scab lesions recorded.

RESULTS

Field experiment 1998

June 1998 was particularly wet with 107mm of rainfall recorded. Consequently, plots which were not sheltered at this time were frequently subject to drainage and a negative SMD for much of the period. In plots which were sheltered during this first drought period the SMD rose slowly to a maximum of 16mm.

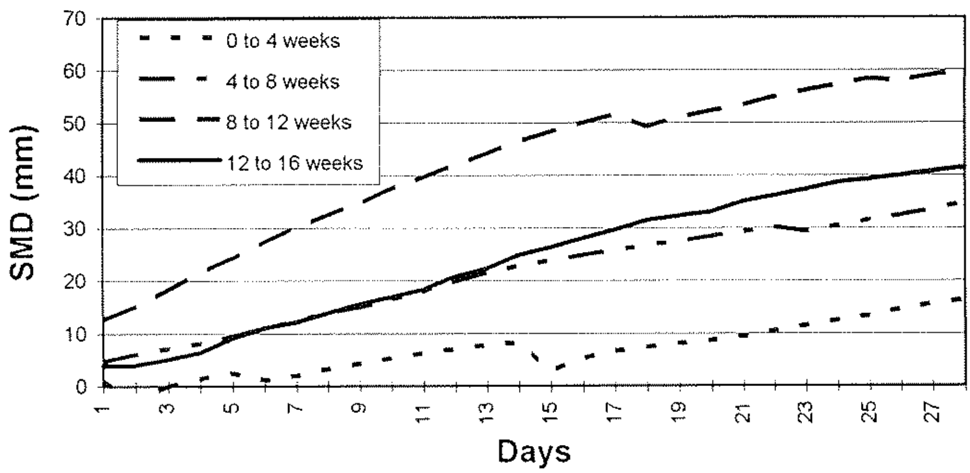
Table 3 shows the rainfall recorded at the site during each drought period and the maximum SMD in the sheltered and unirrigated plots at the end of each respective period. Figure 1 describes the SMD rise during the 28 days of each drought period. The small drops in SMD during drought periods 0-4 and 8-12 weeks were caused by sudden heavy rain falling on the plot before the shelters were able to close.

Appendix 2 describes the irrigation applications in a tabulated form.

Table 3. Rainfall and Maximum SMD

Drought period	Rainfall (mm) during each drought period	Maximum SMD (mm) in sheltered plots.
0-4 weeks	56.3	16
4-8 weeks	35.3	35
8-12 weeks	33.0	60
12-16 weeks	44.3	41

Figure 1 Soil moisture changes during each shelter period



Emergence was complete by 11 June at which time the drought treatments were imposed.

The soil moisture measurements taken at emergence and at the end of each drought period are shown in table 4. It is important to recognise that these measurements relate only to the top 6 cm of soil and are therefore not directly comparable with the SMD's shown in figure 1. The SMD's calculated by 'Irriguide' apply to the whole root zone extending to a maximum depth of 0.6m and were used to schedule irrigation applications. The volumetric measurements were taken so that the effect of the soil moisture status around the tap root could be investigated.

Table 4.

Volumetric water content (%) at the end of each drought period			
week 4	week 8	week 12	week 16*
5.32	5.23	4.30	6.37

* Data produced by a layered soil water model because rain (7mm) falling on the plots the day before the end of the drought period prevented any soil moisture readings.

The mean value at emergence before the treatments were imposed was 17.5%.

The above data show that each drought period succeeded in reducing the soil water content around the carrot roots from 17.5% at the start of the treatments to between 4.3% and 6.4% at the end of each drought period.

Table 5.

	Depth of water falling on each plot (mm) during each period			
	Drought treatment			
Drought Period	0-4 weeks	4-8 weeks	8-12 weeks	12-16 weeks
0-4 weeks	6	82.3	81	56.3
4-8 weeks	78.3	0	96	56.3
8-12 weeks	78.3	72.3	4	91.3
12-16 weeks	78.3	72.3	81	7

Table 5 shows the amount of water falling on each treatment (either as rain or irrigation) during the course of the experiment.

The incidence and severity of common scab are shown in tables 6-10.

Table 6. Percentage roots affected with common scab in category 1 (<0.3% surface area affected)

0-4 Weeks	4-8 Weeks	8-12 Weeks	12-16 Weeks	Significance
3.5	6.5	14.75	5.25	*P*=0.01

SE = 1.87 DF = 9 CV% = 49.9

Table 7. Percentage roots affected with common scab in category 2 (0.3 - 1.5% surface area affected)

0-4 Weeks	4-8 Weeks	8-12 weeks	12-16 Weeks	Significance
1.75	1.75	9.25	1.25	*P*=0.026

SE = 1.71 DF = 9 CV% = 97.8

Table 8. Percentage roots affected with common scab in category 3 (1.5 - 3% surface area affected)

0-4 Weeks	4-8 Weeks	8-12 Weeks	12-16 Weeks	Significance
0.25	1.00	2.25	0.00	*N.S*

SE = 0.534 DF = 9 CV% = 122

Table 9. Percentage roots affected with common scab

0-4 Weeks	4-8 Weeks	8-12 Weeks	12-16 Weeks	Significance
5.5	9.3	26.3	6.5	*P*=0.002

SE = 2.81 DF = 9 CV% = 47.3

Table 10. Mean % surface area affected

0-4 Weeks	4-8 Weeks	8-12 Weeks	12-16 Weeks	Significance
0.027	0.048	0.156	0.019	*P*=0.006

SE = 0.0224 DF = 9 CV% = 71.7

The above data show that common scab was found in all treatment at an incidence ranging from 5.5% to 26.6% root affected. The level of infection was no greater than 3% root surface area in any treatment. There was a consistent and significant increase in common scab levels associated with drought imposed during period 3 (8-12 weeks after emergence). Disease severity followed a similar pattern (Table 10).

Table 11. Percentage roots with fanging

0-4 Weeks	4-8 Weeks	8-12 Weeks	12-16 Weeks	Significance
3.7	2.9	2.8	2.8	*N.S.*

SE = 1.226 DF = 9 CV% = 73.7

The incidence of root fanging was low and was not affected by treatment.

Root yields and root numbers are presented in Tables 11 and 12.

Table 12. Root yield (t/ha)

0-4 Weeks	4-8 Weeks	8-12 Weeks	12-16 Weeks	Significance
35.2	38.1	38.7	34.5	*N.S.*

SE = 3.738 DF = 9 CV% = 20.4

Table 13. Number of roots/ha ('000)

0-4 Weeks	4-8 Weeks	8-12 Weeks	12-16 Weeks	Significance
727	778	800	797	*N.S.*

SE = 59.4 DF = 9 CV% = 15.3

Drought treatment did not effect root number or yield. As all treatments were subjected to 4 weeks of drought yields were low.

Root cracking was not found in this experiment.

Glasshouse Experiment 1998

At 100% emergence the watering treatments were imposed for a period of 12 weeks. At the end of this period the pots were emptied, roots were washed and assessed for common scab. The range of soil moisture measurements taken during the study using a Theta Probe are shown in Table 13.

Table 14. Range of Soil Moisture (%) recorded immediately before next planned irrigation application

	Treatment	Range of volumetric water content (%)
1.	Watered to saturation every 2 days	14.3 - 25.9
2.	Watered to saturation every 4 days	6.3 -19.5
3.	Watered to saturation every 6 days	6.7 - 10.0
4.	Watered to saturation every 8 days	3.1 - 7.7
5.	Watered to saturation every 10 days	2.4 - 5.1

Mean % volumetric moisture content after saturation = 31%

Soil moisture contents fluctuated between 31% (saturated soil) just after watering and the range of figures shown in the table above. Clearly the soil moisture figures recorded in the top 6cm of soil increased with increasing irrigation frequency.

At the end of the study, root assessments revealed a complete absence of common scab in all pots and all treatments.

Potentially there are a number of reasons for the lack of disease symptoms in this experiment:

- All treatments afforded complete control. This may seem unlikely but this possibility will be discussed in a later section.
- Lack of innoculum in the soil despite the fact that soil was taken from the field site where the disease was common.
- Sample too small to pick up the level of disease.
- Glasshouse environment not conducive to disease development (high temperatures).

Clearly it is not possible to determine with any certainty which single, or combination of factors resulted in the lack of disease.

DISCUSSION

The mode of common scab (*Streptomyces scabies*) infection in potatoes has been extensively researched and published in the literature (Adams and Lapwood, 1978). The organism is known to infect lenticels on the developing tubers during a susceptible phase which lasts about 10 days from about 1-2½ weeks after lenticel formation. Research has shown that in dry soils these susceptible lenticels are colonised by actinomycetes (eg *Streptomyces scabies*) and bacterial colonies. In wet soils the actinomycetes are rarely present but bacteria remain scattered over the tuber surface. The absence of the scab organism in wet soils is therefore accepted as the reason for low levels of common scab on the tubers grown in such conditions. This research was the basis of a commercial irrigation strategy for potatoes whereby the soil is kept close to field capacity (i.e. <15mm SMD) during the period when tuber lenticels are susceptible to infection. The hypothesis of this study is that a similar control mechanism may operate for carrot common scab.

1998 Experiments

The data from the 1998 experiment clearly demonstrates that irrigation can reduce the incidence of scab and further that the timing of irrigation may be important. In the field experiment disease levels were higher where all irrigation and rainfall was excluded during the 4 weeks period 8-12 weeks after emergence. Similar 4 weeks drought periods (0-4, 4-8 and 12-16 weeks) resulted in significantly lower disease levels. However drought during weeks 8-12 was also associated with the highest SMDs (Table 3) and lowest soil moisture measurements (Table 4). Maximum SMDs at the end of each drought period differed because of variations in rates of evapotranspiration during the preceding 4 weeks which were also influenced by the growth stage of the crop (i.e. a small crop grown in a dull humid environment will develop a lower SMD than a large crop grown in hot sunny weather). It is therefore possible that the higher disease levels in this treatment were a function both of drought timing and drought severity. This possibility must be considered when developing a commercial irrigation strategy.

The glasshouse experiment was designed to evaluate whether the frequency of irrigation affected disease development. In the first year of this study it was apparent that the majority of scab lesions were around the neck of the root where the soil is driest. It was postulated in the 1997 report (Appendix 4) that frequent watering may keep the soil around the neck of the carrot moist and thereby prevent infection. Unfortunately no disease was recorded in the glasshouse study. The possible reasons for the absence of disease were eluded to earlier.

The absence of disease in this experiment was not due to a lack of drought conditions as Tables 4 and 14 indicate that the lowest soil moisture measurements were found in the glasshouse study. It could be postulated however, that disease development required low soil moisture over an extended period of time. If this were the case then it would be reasonable to expect higher levels of disease in the field experiment where drought was allowed to develop over 28 days whereas in the glasshouse study the soil was saturated at a maximum 10 day interval. However, the absence of disease can not necessarily be attributed to control achieved by the watering treatments. The other factors stated earlier, i.e. lack of innoculum, size of sample and the potential effects of a glasshouse environment, may be the true cause. Therefore, further studies would be required to determine whether irrigation frequency affected disease development.

DISCUSSION OF THE WHOLE PROJECT

Before considering guidelines for controlling scab with irrigation it is necessary consider three questions.

1. Is there sufficient evidence to confirm that irrigation can reduce the incidence of scab?

   In both years of this study the incidence of common scab was reduced where irrigation was applied. These results are in accord with earlier work done at Gleadthorpe (Groves & Bailey, 1994) and more recently in Denmark (Sorensen *et al.*, 1997). It therefore seems reasonable to conclude that irrigation is an appropriate method by which growers can control carrot scab.

2. Is there a crop growth stage particularly associated with disease infection?

   In the 1998 season of this study there was a significant effect of irrigation timing on disease control (Tables 6-10) with drought during the 8-12 week period after emergence associated with higher disease incidence. Irrigation applied during this period reduced disease incidence from 26.3% to between 5.5 and 9.3%. However, as discussed earlier, it must be noted that this treatment was also associated with the highest SMDs. It is therefore not possible to determine whether the higher levels of disease were solely a function of drought timing or were also influenced by drought severity. Sorensen *et al* (1997), reported an effect of irrigation timing on disease control. In their study drought during the 1 to 3 true leaf stage (approx. 2-4 weeks after emergence) resulted in higher disease levels. However, this study did not measure soil moisture conditions during the various drought stages and it is therefore possible that this period was also associated with the greatest drought severity. Earlier studies at Gleadthorpe (Groves & Bailey 1994), and the data from the first season of this experiment failed to define periods sensitive to disease infection. Clearly the finding from these studies leave some questions unanswered. However they do identify that periods of drought up to 12 weeks after emergence may result in increased levels of common scab.

3. What soil moisture conditions are associated with infection?

   Within the course of this study soil moistures were monitored in each treatment. It is therefore possible to describe the conditions which gave rise to disease control in each season. This information will be used later when formulating a commercial strategy for disease control.

In the light of information available we must now consider how irrigation should be managed to optimise disease control.

In the experiments reported here, the full irrigation treatments sought to maintain SMD below 15mm from sowing until the 7 true leaf stage subsequently below 25mm (except where drought was imposed in 1998). This intensive programme gave significant disease control in both seasons. A similar intensive programme used in earlier work at Gleadthorpe (Groves & Bailey, 1994) also gave significant disease control (unirrigated 29% root surface area affected, fully irrigated 12% root surface area affected). Similarly in recent Danish work (Sorensen *et al*, 1997) full irrigation reduced the incidence of disease from 11% to 4% roots affected. None of these studies reported the complete control of common scab. Water management may never give complete control but it remains a possibility that an even more intensive programme may reduce disease levels further. Clearly such an approach would present considerable practical problems.

When considering how to manage irrigation we must examine whether irrigation can be restricted to specific times in the season when disease infection occurs but relaxed during other non-sensitive periods? As discussed earlier the 1998 data reported a significant increase in disease where rainfall and irrigation was excluded from the crop during a period 8-12 weeks after emergence. Sorensen studied the effect of 4 drought periods (1-3 true leaves, 4-6 true leaves, 3 weeks in July/August and 3 weeks before harvest). Here only drought during the 1-3 true leaf stage (approximately 2-4 weeks after emergence) increased the incidence of disease. However, it remains possible in these cases that disease incidence was affected by drought severity and drought timing. Notwithstanding this, these studies have identified that the 12 week period after emergence presents the greatest risk of disease infection.

COMMERCIAL IRRIGATION STRATEGY

The strategy described below is based on the information available from the two year study at Gleadthorpe and the work done in Denmark. It accommodates the levels of soil moisture recorded within the experiments and the associated levels of common scab. It is designed to afford the level of control achieved within the experiments reviewed here, whilst minimising the amount and frequency of irrigation.

In the light of the results reported here the following schedule is proposed.

- Irrigate to maintain the SMD below 15mm until 8 weeks after emergence

Then

- Irrigate to maintain the SMD below 30mm between weeks 8 and 12

Then

- Irrigate to maintain the SMD below 40mm until harvest

Clearly this is an intensive schedule which will present many growers with logistical problems. The greatest challenge will be to maintain SMDs below 15mm whilst ensuring metalaxyl applied to control cavity spot is not leached from the upper soil layers. The minimum practical application rate for the majority of irrigation equipment is 10mm. To achieve good control of common scab it is recommended that 10mm is applied whenever the SMD reaches 15mm during the first 8 weeks of growth. If cavity spot is not an issue, then up to 15mm may be applied during this period. After the 8 week stage the application rate can be safely increased to 25mm to keep the SMD below 30 or 40mm.

Irrigation in excess of this schedule may reduce the levels of scab further. However, this may be at the expense of other quality, pest or disease problems.

Appendix 1

Cropping details field experiment 1998

Previous cropping	1997 Fallow 1996 Fallow 1995 Potatoes
Soil Series	Cuckney
Soil texture	Loamy sand over sand
Soil analysis	pH, 6.7 P, 48 mg/l (4) K,101 mg/l (1) Mg, 61 mg/l (2)
Cultivations	Chisel plough, Power harrow, Bed formed and harrowed
Cultivar	Narbonne
Planting date	20/5/98
Fertilisers	Nitrogen @ 120 kg/ha as 232 kg/ha Extra N (34.5%) Phosphate @ 50 kg/ha P as 109 kg/ha Triple Super Phosphate (46%) Potassium @ 100 kg/ha K as 200 kg/ha Muriate of potash (60%) Sodium @ 150 kg/ha as 417 kg/ha Supersalt (36%) Boron @ 2 kg/ha as 11.4 kg/ha Solubor (21%)
Pesticides	8 May 1440 g/ha Glyphosate as 4 l/ha Roundup 20 May 2.35 kg Clorfenvinphos as 9.8 l/ha Sapecron 21 May 495 g Linuron as 1.1l/ha Linuron flowable 17 July and 21 July 840 g/ha Chlorpropham + 1680 g/ha Pentanochlor as 5.6 l/ha Atlas Brown
Harvest	20 October 1998

Field experiment 1998 - Irrigation applications (mm) by date and amount

Date	Droughted for 4 weeks after emergence then fully irrigated	Droughted from week 4 -8 after emergence then fully irrigated	Droughted from week 8-12 after emergence then fully irrigated	Droughted from week 12-16 after emergence then fully irrigated
26 Jun	-	11	11	11
06 Jul	-	11	11	11
10 Jul	11	-	7	7
15 Jul	11	-	5	5
22 Jul	11	-	11	11
23 Jul	4	-	4	4
31 Jul	10	-	10	10
06 Aug	6	17	-	6
11 Aug	6	10	-	6
14 Aug	12	12	-	12
18 Aug	13	13	-	13
28 Aug	11	11	-	11
04 Sep	-	-	12	-
07 Sep	-	-	11	-
11 Sep	-	-	12	-
22 Sep	12	12	12	-
Total	107	97	106	107

Appendix 3

Schedule of watering treatments, glasshouse experiment 1998

Date	Every 2 days	Every 4 days	Every 6 days	Every 8 days	Every 10 days
02/07/98	y				
04/07/98	y	y			
06/07/98	y		y		
08/07/98	y	y		y	
10/07/98	y				y
12/07/98	y	y	y		
14/07/98	y				
16/07/98	y	y		y	
18/07/98	y		y		
20/07/98	y	y			y
22/07/98	y				
24/07/98	y	y	y	y	
26/07/98	y				
28/07/98	y	y			
30/07/98	y		y		y
01/08/98	y	y		y	
03/08/98	y				
05/08/98	y	y	y		
07/08/98	y				
09/08/98	y	y		y	y
11/08/98	y		y		
13/08/98	y	y			
15/08/98	y				
17/08/98	y	y	y	y	
19/08/98	y				y
21/08/98	y	y			
23/08/98	y		y		
25/08/98	y	y		y	
27/08/98	y				
29/08/98	y	y	y		y
31/08/98	y				
02/09/98	y	y		y	
04/09/98	y		y		
06/09/98	y	y			
08/09/98	y				y
10/09/98	y	y	y	y	
12/09/98	y				
14/09/98	y	y			
16/09/98	y		y		
18/09/98	y	y		y	y
20/09/98	y				
22/09/98	y	y	y		
24/09/98	y				

Appendix 4

Interim report
1997 experiment

Project title: CARROTS: The control of common scab with irrigation

Report: Interim report (December 1997)

Project number: FV 195

Project leader: Simon Groves
ADAS Gleadthorpe Research Centre
Meden Vale
Mansfield
Notts NG20 9PF

Location: ADAS Gleadthorpe

Project co-ordinator: Mr P Knights

Date of commencement: April 1997

Date of completion: December 1998 (ongoing)

Key words: Carrots, common scab, irrigation.

PRACTICAL SECTION FOR GROWERS

Common scab is, as one might expect from its name, a common problem for carrot growers. It is caused by the organism *Streptomyces scabies* which can be found in most arable soils and is also known to cause scab in potatoes. Previous research has shown that *Streptomyces scabies* is less common in wet soils and that effective control of the disease in potatoes can be achieved by the timely application of irrigation. The only previous work that has been done on the control of carrot scab took place at ADAS Gleadthorpe in the late 1980's. In a series of experiments over a number of years carrot scab was controlled by irrigation in a single season. No other research has linked carrot scab control with irrigation. These experiments were not designed to study scab control, but data from this work together with anecdotal evidence from growers suggests that irrigation applied early in the crop's growth may provide the best control. The experiment conducted at ADAS Gleadthorpe in 1997 formed part of a two year study designed to investigate the effect of irrigation and irrigation timing on common scab control with the aim of developing a commercial irrigation strategy for growers.

The experiment was conducted on a light loamy sand site using the scab susceptible variety Narbonne. Automatic rain shelters were used to exclude rainfall for 4 separate 3 week drought periods from drilling up to 12 weeks after drilling (i.e. 0-3 weeks, 3-6 weeks, 6-9 weeks, 9-12 weeks). Additionally three sub-treatments of nil, full and sub-optimal irrigation were applied during each drought period. The rain shelters protected plots from rainfall by automatically moving over designated plots as soon as an electronic sensor detected rain. When rainfall stopped the shelters moved back thus ensuring that the crop micro climate remained largely unaffected.

The crop was grown during a predominately wet period of the season which, but for the use of the rain shelters, would have ruined the experiment. Soil moistures were recorded by taking gravimetric measurements of the soil immediately surrounding the carrots and by monitoring the whole root zone using the computer irrigation scheduling program 'Irriguide'.

At harvest common scab was found in all treatments with the highest incidence recorded at 25% roots affected. The severity of infection was generally low with most roots having less than 1.5% surface area affected.

The results from the first year of this study clearly show a significant reduction in the incidence of common scab where irrigation was applied. This finding is in accord with both the previous study at Gleadthorpe, and grower experience. Trends within the data also suggest that disease control improved as the level of soil moisture immediately adjacent to tap root increased. This infers that good control may require the surface soil to be close to field capacity. However, more data will be required before any firm conclusion can be drawn. If surface soil moisture is influential in the development of scab then the frequency of irrigation is likely to affect control. It is possible the more frequent application of small quantities of water may prevent the surface layer drying out thereby improving disease control. It is proposed that the 1998 experimental work investigates this possibility.

The data did not identify a particular period of the season associated with disease development. However, it would be premature to assume that, based on a single year's data, no such period exists. This element of the study will be repeated in 1998 with some treatment amendments which should increase the contrast between droughted and irrigated treatments thus improving the chance of identifying susceptible periods.

In summary the first year of this study has produced useful data in a season when the use of the rain shelter facility proved to be invaluable. It has confirmed that irrigation provides a means of controlling common scab and has highlighted other avenues of further investigation which will be addressed in 1998.

REPORT OF EXPERIMENT RESULTS

MATERIALS AND METHODS

The experiment was sited at ADAS Gleadthorpe on a loamy sand soil (Cuckney Series) with a low water holding capacity. The scab susceptible variety Narbonne was sown into small plots situated under an automatic rain shelter facility. These shelters protect plots from rainfall by automatically moving over designated plots as soon as an electronic sensor detects rainfall. When rainfall stops the shelters move back thus ensuring that the crop micro climate remains largely unaffected.

At drilling the soil was close to field capacity in all plots. Sufficient seeds were sown to achieve a target population of 1 million plants per hectare using a Singulaire drill set with 4 drill units each fitted with a 3 line coulter to produce 4 multirows per 1.72m bed. Appropriate fertilisers and pesticides were applied (appendix 1). Immediately after drilling drought and irrigation treatments were imposed (Tables 1 and 2).

Table 1 Drought treatments

Main treatments
1. Sheltered from rainfall for the first 3 weeks after drilling.
2. Sheltered from rainfall from the end of the 3rd to the end of the 6th week after drilling.
3. Sheltered from rainfall from the end of the 6th to the end of the 9th week after drilling.
4. Sheltered from rainfall from the end of the 9th to the end of the 12th week after drilling.

Full irrigation was applied during periods when the plots were not sheltered.

Each main plot (60m²) was subdivided into three sub-plots of 12m² each with suitable guarding. This produced a split-plot design experiment with four replicates of each main treatment (16 main plots) and 48 sub-plots (16 main plots x 3 sub-plots). The sub-plot irrigation treatments were imposed **only** during the period when the main plots were sheltered.

Table 2. Irrigation treatments

Sub-plot treatments
1. Unirrigated.
2. Fully irrigated.
3. Irrigated with half the amount applied to sub-treatment 2 (sub-optimal irrigation).

Full irrigation was designed to maintain the soil close to field capacity i.e. a soil moisture deficit (SMD) less than 15mm early in the season and less than 25mm after the 7 true leaf stage. The computer program 'Irriguide' was used to schedule irrigation.

The moisture status of the soil immediately adjacent to the tap root was measured gravimetrically from soil samples taken during and at the end of each drought period. The depth to which soil was sampled varied with the length of the tap root. Soil moisture deficits of the whole rooting zone were monitored by 'Irriguide'.

All plots were harvested by hand 17 weeks after sowing. The tops were removed and the total yield and root number from each plot was recorded. A sub-sample of 75 roots was taken from each plot, washed and assessed for common scab, cracking and fanging. Common scab was assessed into four categories using the NIAB key for cavity spot; (1) nil; (2) <1.5% surface area affected; (3) 1.5% to 3% surface area affected; (4) more than 3% surface area affected. These data were used to calculate the incidence and severity of infection using the formula:

(No in category 1 x 1) + (No in category 2 x 2) + (No. in category 3 x 3) + (No in category 4 x 4).

The percentage roots affected by fanging and cracking were recorded. All data were subjected to analysis of variance using the Genstat 5 program.

RESULTS

The three week period immediately after sowing was particularly wet with rain falling every day for the first 16 days of the 21 day period. A total of 96.7mm was recorded during this time. Consequently, plots which were not sheltered at this time were frequently subject to drainage and a negative SMD for much of the period. Where plots were sheltered and unirrigated the SMD rose slowly to a maximum of 16mm. Clearly the dull, overcast weather during this period prevented rapid drying of the soil even where rainfall was excluded.

Table 3 shows the rainfall recorded at the site during each drought period and the maximum SMD in the sheltered and unirrigated plots at the end of each respective period.

Figures 1-12 in appendix 2 describe in detail the timing and amounts of irrigation, and the changes in SMD. Appendix 3 describes the irrigation applications in a tabulated form.

Table 3. Rainfall and Maximum SMD

Drought period	Rainfall (mm) during each drought period	Maximum SMD (mm) in sheltered plots with nil irrigation..
0-3 weeks	96.7	16
3-6 weeks	34.3	26
6-9 weeks	17.5	42
9-12 weeks	50.0	52
TOTAL	198.5	

The crop began to emerge two weeks after sowing and emergence was complete after three weeks. Table 4 shows the range of tap root lengths and number of true leaves at the end of each drought period.

Table 4. Average tap root length and true leaf number at the end of each drought period

Drought period	Average tap root (mm) lengths	Average true leaf number
0-3 weeks	<10	0
3-6 weeks	30	3.5
6-9 weeks	100	10.5
9-12 weeks	170	full ground cover

The gravimetric soil moisture measurements taken at the end of each drought period were analysed and are shown in tables 5-8. It is important to recognise that these measurements relate only to the soil immediately adjacent to the tap root and are therefore not directly comparable with the SMD's shown in appendix 2. The SMD's calculated by 'Irriguide' apply to the whole root zone extending to a maximum depth of 0.6m and were used to schedule irrigation applications. The gravimetric measurements were taken so that the effect of the soil moisture status around the tap root could be investigated.

Table 5. Gravimetric soil moisture content (% by weight) at the end of drought period ONE

Drought treatment	Irrigation treatment: Unirrigated	Fully irrigated	Sub-optimally irrigated	Mean
1. 0-3 weeks	6.01	6.68	6.44	6.38
2. 3-6 weeks	6.23	6.37	6.41	6.34
3. 6-9 weeks	7.35	7.49	7.28	7.37
4. 9-12 weeks	7.65	8.32	7.70	7.89
				N.S
Mean	6.81	7.22	6.96	N.S

SE: irrigation means 0.158 (24 df); timing means 0.533 (9 df)

Table 6. Gravimetric soil moisture content (% by weight) at the end of drought period TWO

Drought treatment	Irrigation treatment: Unirrigated	Fully irrigated	Sub-optimally irrigated	Mean
1. 0-3 weeks	6.61	6.76	5.93	6.43
2. 3-6 weeks	3.27	4.25	3.88	3.80
3. 6-9 weeks	6.07	6.45	6.19	6.23
4. 9-12 weeks	6.31	6.57	6.83	6.57
				$p = <0.01$
Mean	5.56	6.01	5.71	N.S

SE: irrigation means 0.179 (24 df); timing means 0.435 (9 df)

Table 7. Gravimetric soil moisture content (% by weight) at the end of drought period THREE

	Irrigation treatment			
Drought treatment	Unirrigated	Fully irrigated	Sub-optimally irrigated	Mean
1. 0-3 weeks	7.43	7.66	7.73	7.60
2. 3-6 weeks	6.13	5.83	5.75	5.91
3. 6-9 weeks	3.64	6.49	5.17	5.10
4. 9-12 weeks	6.37	6.77	7.08	6.74
				p=<0.001
Mean	5.89	6.69	6.43	p=<0.001

SE: irrigation means 0.104 (24 df); timing means 0.283 (9 df)

Table 8. Gravimetric soil moisture content (% by weight) at the end of drought period FOUR

	Irrigation Treatment			
Drought treatment	Unirrigated	Fully irrigated	Sub-optimally irrigated	Mean
1. 0-3 weeks	8.84	8.94	9.03	8.94
2. 3-6 weeks	7.36	6.95	7.44	7.25
3. 6-9 weeks	8.14	8.39	7.99	8.17
4. 9-12 weeks	5.96	8.29	7.37	7.21
				N.S
Mean	7.58	8.14	7.96	p=<0.05

SE: irrigation means 0.124 (24 df); timing means 0.437 (9 df)

Although the data show some natural variability due to the nature of the technique, important differences were apparent. In all cases measurements taken at the end of a drought period where no irrigation had been applied produced the lowest value, albeit this difference was not always significant. This confirms that the drought treatments were effective. The data also show that the plots which were sheltered during period one became progressively wetter as the season progressed despite the fact that they were irrigated in line with the criteria set out for all other treatments. A possible reason for this trend is explained by the differences in plant populations between the shelter treatments (Table 9).

Table 9. Number of roots/ha ('000)

Drought treatment	Irrigation Treatment: Unirrigated	Fully irrigated	Sub-optimally irrigated	Mean
1. 0-3 weeks	326	355	303	328
2. 3-6 weeks	826	1015	930	923
3. 6-9 weeks	909	872	907	896
4. 9-12 weeks	1002	991	985	993
				p = <0.001
Mean	766	808	781	N.S

SE: irrigation means 29.5 (24 df); timing means 70.3 (9 df)

These data indicate a significantly lower plant population at harvest where plots had been sheltered during the first 3 weeks after sowing. The cause of this difference is unknown. The possible causes for this effect are (1) the presence of the shelter over the plots due to the persistent rainfall may have altered the micro climate which in turn may have affected plant growth possibly by encouraging 'damping-off' diseases; (2) the effect on the structure of the soil surface from the application of irrigation prior to emergence on the fully and sub-optimally irrigated plots (3) withholding of all water and the subsequent desiccation of the soil surrounding the seedling on the unirrigated plots.

The consequence of a reduced population was reduced water use resulting in an increased soil moisture content as the season progressed.

The incidence and severity of common scab are shown in tables 10 and 11.

Table 10. Percentage roots with common scab

Drought treatment	Irrigation Treatment: Unirrigated	Fully irrigated	Sub-optimally irrigated	Mean
1. 0-3 weeks	25.0	8.7	8.0	13.9
2. 3-6 weeks	11.7	13.3	19.0	14.7
3. 6-9 weeks	19.7	11.3	15.0	15.3
4. 9-12 weeks	22.7	18.0	15.3	18.7
				N.S
Mean	19.8	12.8	14.3	p = <0.05

SE: irrigation means 1.97 (24 df); timing means 4.15 (9 df)

Table 11. Common scab severity disease index (Scale of 75-300)

	Irrigation Treatment			
Drought treatment	Unirrigated	Fully irrigated	Sub-optimally irrigated	Mean
1. 0-3 weeks	93.8	81.5	80.8	85.3
2. 3-6 weeks	84.0	85.5	89.3	86.3
3. 6-9 weeks	92.0	83.3	87.0	87.4
4. 9-12 weeks	92.5	88.0	87.3	89.3
				N.S
Mean	90.6	84.6	86.1	p = <0.05

SE: irrigation means 1.60 (24 df); timing means 3.59 (9 df)

Analysis of the data indicated that the significant (p = <0.05) factor influencing disease development was the presence and level of irrigation and not the time of its application. Full irrigation throughout the season reduced the incidence of scab to 13% compared with 20% where water was withheld for any period during the 12 weeks after sowing (Table 10). Disease severity exhibited a similar pattern. Sub-optimal irrigation was associated with intermediate levels of scab.

The incidence of fanging is reported in table 12. Fanging was influenced by drought timing and irrigation with the highest incidence associated with sub-optimal irrigation during weeks 0-3 (p = <0.01). The reason for this particular treatment showing a higher incidence is not clearly understood, but the effect was consistent across all four replicates. Root cracking was observed at extremely low levels (<0.2%) and was not a factor in the experiment.

Table 12. Percentage roots with fanging

Drought treatment	Irrigation Treatment Unirrigated	 Fully irrigated	 Sub-optimally irrigated	Mean
1. 0-3 weeks	2.20	0.85	6.48	3.18
2. 3-6 weeks	1.08	0.91	0.40	0.80
3. 6-9 weeks	1.43	2.31	1.26	1.67
4. 9-12 weeks	1.32	1.27	1.02	1.20
				$p = <0.05$
Mean	1.51	1.33	2.29	$p = <0.05$

SE: irrigation means 0.250 (24 df); timing means 0.519 (9 df)

Total root yields were also recorded and are presented in Table 13.

Table 13. Total root yield (t/ha)

Drought treatment	Irrigation Treatment Unirrigated	 Fully irrigated	 Sub-optimally irrigated	Mean
1. 0-3 weeks	24.0	22.7	20.2	22.3
2. 3-6 weeks	41.6	46.6	45.8	44.7
3. 6-9 weeks	43.0	50.9	45.8	46.5
4. 9-12 weeks	43.8	52.2	46.3	47.4
				$p = <0.01$
Mean	38.1	43.1	39.5	$p = <0.05$

SE: irrigation means 1.25 (24 df); timing means 3.60 (9 df)

The significantly lower yields associated with drought period one were a function of lower plant populations in these treatments. As expected irrigation significantly increased yield at all other times. There was, on average, a 12% yield penalty associated with withholding all water for a 3 week period.

DISCUSSION

The mode of common scab (*Streptomyces scabies*) infection in potatoes has been extensively researched and published in the literature (Adams and Lapwood, 1978). The organism is known to infect lenticels on the developing tubers during a susceptible phase which lasts about 10 days from about 1-2½ weeks after lenticel formation. Research has shown that in dry soils these susceptible lenticels are colonised by actinomycetes (eg *Streptomyces scabies*) and bacterial colonies. In wet soils the actinomycetes are rarely present but bacteria remain scattered over the tuber surface. The absence of the scab organism in wet soils is therefore accepted as the reason for low levels of common scab on the tubers grown in such conditions. This research was the basis of a commercial irrigation strategy for potatoes whereby the soil is kept close to field capacity (i.e. <15mm SMD) during the period when tuber lenticels are susceptible to infection.

No such intensive investigations have been conducted on carrot scab infection. It is possible that the moisture status of soils has the same effect on disease development in carrots as seen in potatoes. This is by no means certain however, as Lapwood *et al* (1976) found no relation between soil moisture and common scab in red beet.

Prior to the experiment reported here no work had been done to determine whether irrigation can control carrot scab or if infection is sensitive to growth stage. However, as stated earlier yield response irrigation studies at Gleadthorpe have recorded scab control where irrigation was applied (Groves and Bailey, 1994).

The results of the first year of this experiment have clearly confirmed that irrigation can reduce the level of scab (Tables 10 and 11). Trends within the data also suggest that the wetter the soil the lower the level of scab. This is suggested by the lower levels of scab where full irrigation was applied compared with sub-optimal irrigation. Also the lowest scab levels occurred in irrigated treatments where plant populations were low and recorded gravimetric soil water contents were generally greater than other irrigated treatments (Tables 5-8).

This trend occurred even though the SMD in the fully irrigated treatments was very low throughout the season due to both rainfall and irrigation applications (Appendix 2). There are, however, obvious dangers in maintaining the soil so close to field capacity. These include water-logging, leaching of nutrients etc. Probably the largest potential problem, however, is the possibility of leaching metalaxyl applied to control cavity spot. It is known that metalaxyl is easily leached and although it is possible to carefully schedule water applications so that irrigation alone does not cause drainage, heavy rainfall after an irrigation event would undoubtedly bring the soil profile beyond field capacity. Clearly this potential problem will need to be addressed when developing a commercial strategy for scab control.

The results did not identify a sensitive period for disease infection within the 12 weeks of this study. There was also no apparent trend in the data as the highest incidence of scab was associated with drought at 0-3 weeks with the next highest figure associated with drought at 9-12 weeks. However, it would be premature to conclude from the results of a single year's data that there is no timing effect. Indeed a recently published study from Denmark (Sorensen *et al*, 1997) reported that drought at the 1-3 leaf stage was associated with increased scab levels. Clearly this issue must be addressed again in the 1998 experiment, the format of which is proposed in the following section of this report.

The location of scab lesions on affected carrots suggests an additional factor which may have influenced disease control. The majority of lesions in this experiment occurred close to the neck of the carrot. Whilst growing, this area of the tap root would be very close to or at the soil surface. The soil surface is subject to water losses both from plant abstraction and surface evaporation. Evaporation can dry the surface soil beyond the maximum achievable by plant abstraction alone. Hence the soil surface is often drier than the rest of the profile as is confirmed by the relatively low gravimetric soil moisture contents measured in this experiment. It is therefore possible that the high incidence of lesions around the neck of carrots is related to the rapid drying of the soil surface. The possibility therefore arises that the frequency of water applications may influence scab infection. Frequent applications of small amounts of irrigation may reduce the incidence of such lesions. Again, this issue should be addressed in the 1998 experiment.

Although the experiment was not designed to study the effects of drought on carrot yield, it is noteworthy that the absence of irrigation or rainfall for a 3 week period reduced yields by 12% below the fully irrigated yield. This confirms that carrots are very sensitive to water stress.

RECOMMENDATIONS FOR 1998 EXPERIMENT

There are 3 main issues which should be addressed in the 1998 experiment.

1. Irrigation timing

The results of the first year of this project did not identify growth stages particularly sensitive to disease infection and it is therefore important to repeat this element of the study in year two. It is proposed that the 1997 field experiment be repeated under the automatic rain shelters at Gleadthorpe but that the treatment design should be amended. The changes proposed are as follows:-

- Increase the length of drought periods to 4 weeks. This will serve to extend the period of crop growth under study and increase the severity of water stress in each drought period.
- Omit the sub-treatments applied during each drought period but increase the frequency of irrigation applied at other times. There were trends in the 1997 data which suggested that the best control was achieved where soil around the carrot root was wettest. The intention would therefore be to apply irrigation more regularly in smaller doses so that the surface layers remained moist.
- To initiate the drought treatments after germination and not sowing. It is believed that the low plant populations in drought period one plots of the 1997 experiment were due to the application of irrigation by watering can in sub-treatments and that this method adversely affected the soil surface structure.

These changes would increase the contrast between droughted and non-droughted treatments during the season, thus providing a greater opportunity to test the effect of drought timing on common scab development.

2. Irrigation frequency

This report has postulated that the frequency of irrigation affects the soil surface moisture which in turn affects scab development. It is proposed that a series of pot tests be conducted in year 1998 to test this theory.

Carrots will be grown in a glasshouse in soil taken from the trial site. Water would be applied at a range of frequencies (e.g. every day to every 7 days) in a fully replicated experiment. This work should identify any effect associated with irrigation frequency.

3. The level of soil moisture required to control common scab

It is proposed that soil moisture be regularly recorded in both the experiments described above. This information, together with that already collected in 1997, should provide the basis for the development of a commercial irrigation strategy.

REFERENCES

ADAMS, M.J. & LAPWOOD, D.H. (1978). Studies on the lenticel development, surface microflora and infection by common scab (*Streptomyces scabies*) of potato tubers growing in wet and dry soils. *Annals of Applied Biology*, **90**, pp 335-343.

BAILEY, R.J. (1990). Irrigated Crops and their Management. *Farming Press* pp192.

GROVES, S.J. & BAILEY, R.J. (1994). The effect of irrigation upon the root yield and incidence of common scab of carrots. *Aspects of Applied Biology* **38** pp217-221.

LAPWOOD, D.H., ADAMS, M.J., CRISP, A.P. (1976). The susceptibility of red beet cultivars to *Streptomyces scabies*. Plant Pathology **25** pp.31-33.

LAPWOOD, D.H., WELLINGS, L.W. & HAWKINS, J.H. (1973). Irrigation as a practical means of controlling common scab (*Streptomyces scabies*). *Plant Pathology* **22** pp 35-41.

SØRENSEN, J.N, JØRGENSEN,U., KÜHN, B.F. (1997). Drought effects on the marketable and nutritional quality of carrots. *Journal of Science Food and Agriculture* 74 pp 379-391.

APPENDIX 1
Cropping details

Previous cropping	1996 Fallow 1995 Potatoes 1994 Linseed
Soil Series	Cuckney
Soil texture	Loamy sand over sand
Soil analysis	pH = 7.0; P = 45 (index 3); K = 102 (index 1); Mg = 99 (index 2); % organic matter = 2.13
Cultivations	Chisel ploughed, bed formed followed by a narrow blench
Cultivar	Narbonne
Planting date	18 June
Seed fertilisers	Nitrogen @ 80 kg/ha as 232 kg/ha Extra N (34.5%) Phosphate @ 50 kg/ha P as 109 kg/ha Triple Super Phosphate (46%) Potassium @ 120 kg/ha K as 200 kg/ha Muriate of potash (60%) Sodium @ 150 kg/ha as 417 kg/ha Supersalt (36%) Boron @ 2 kg/ha as 9.6 kg/ha Solubor (21%)
Pesticides	17 June 1440 g/ha glyphosate as 4 l/ha Roundup 17 July and 21 July 840 g/ha Chlorpropham + 1680 g/ha pentanochlor as 5.6 l/ha Atlas Brown 28 July and 5 September 1050 g/ha triazophos as 2.5 l/ha Hostathion
Harvest	13 October

APPENDIX 2

Figure 1

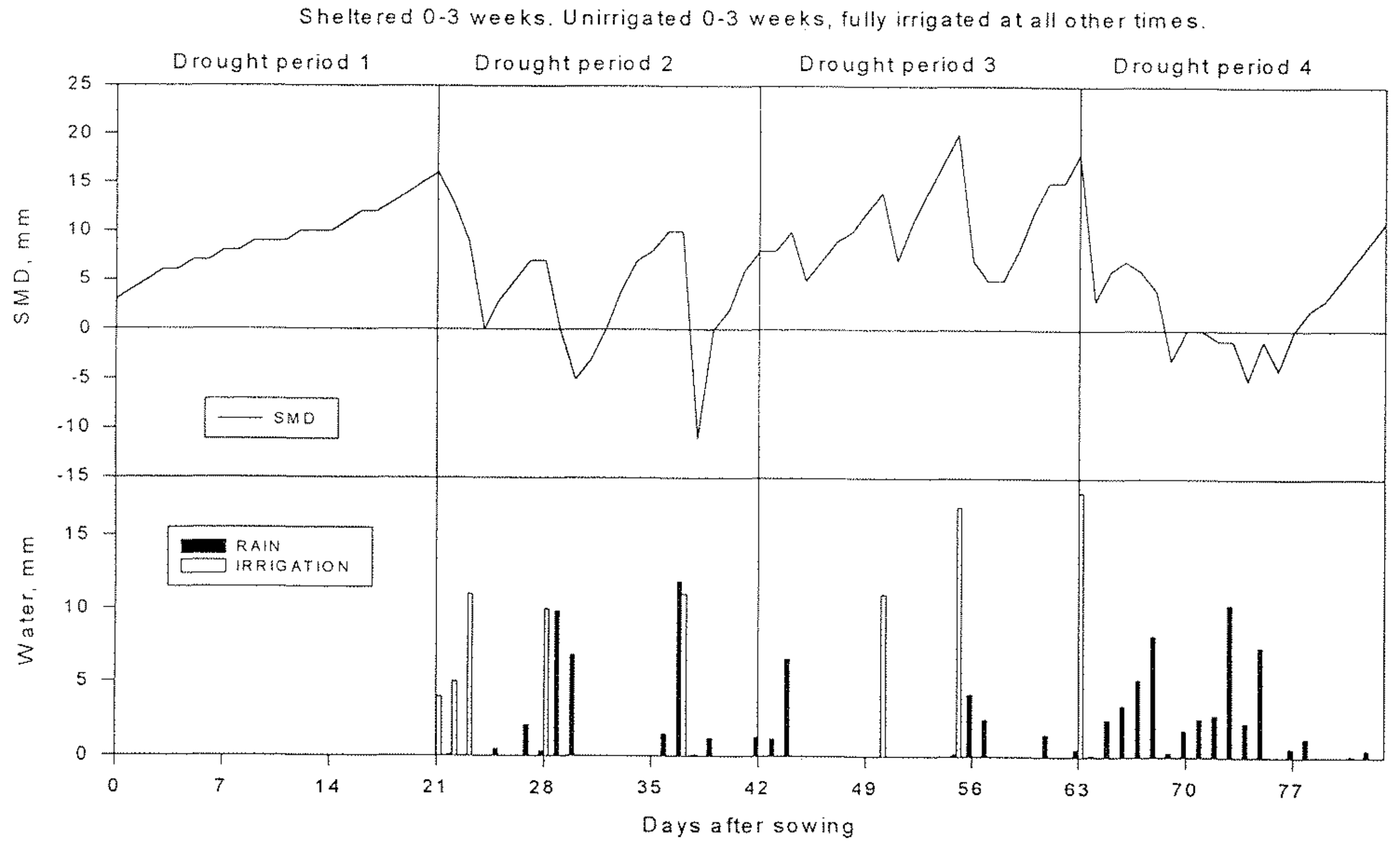
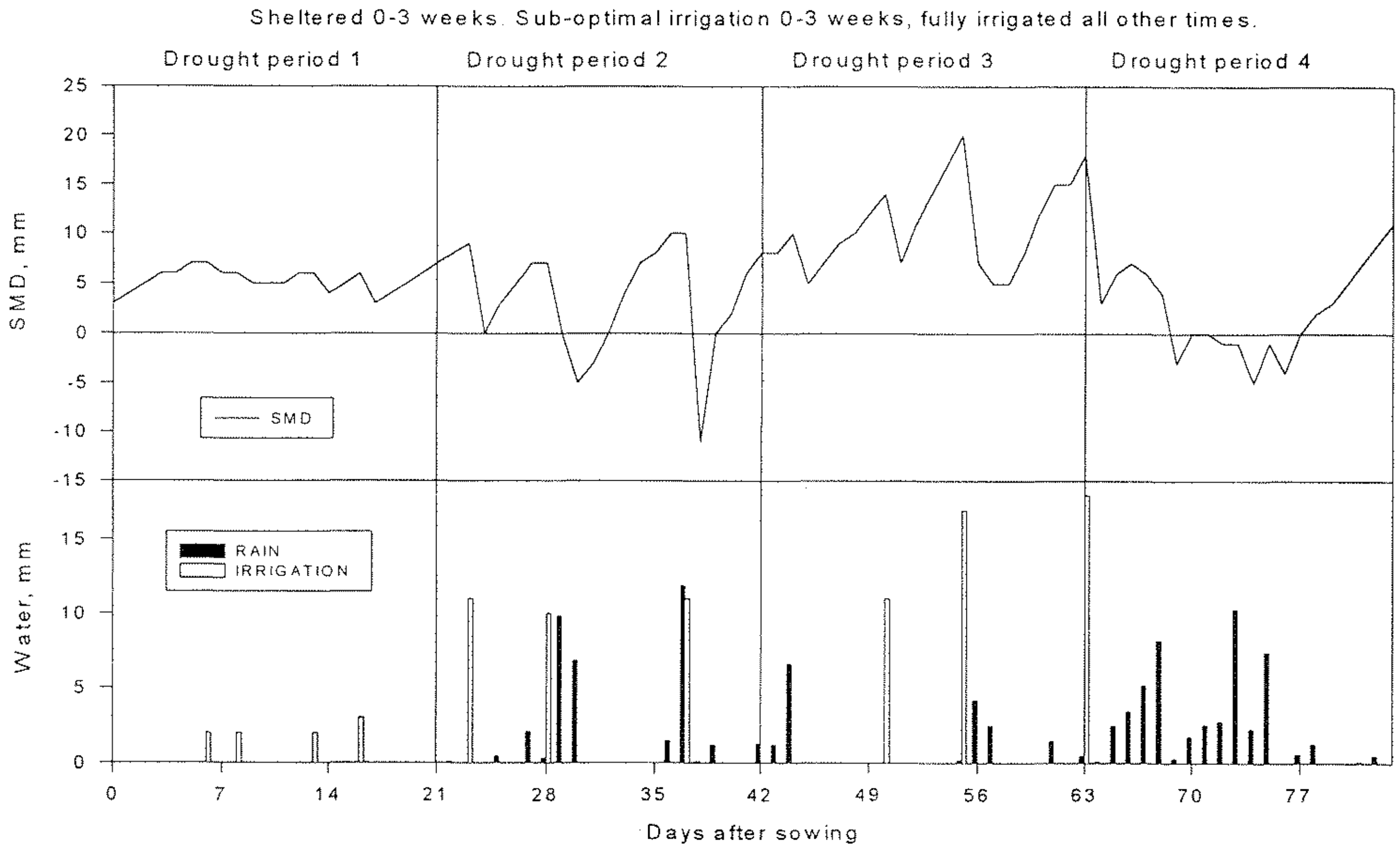


Figure 2



Sheltered 0-3 weeks. Sub-optimal irrigation 0-3 weeks, fully irrigated all other times.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
Water, mm
SMD
RAIN
IRRIGATION
25
20
15
10
5
0
-5
-10
-15
15
10
5
0
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 3

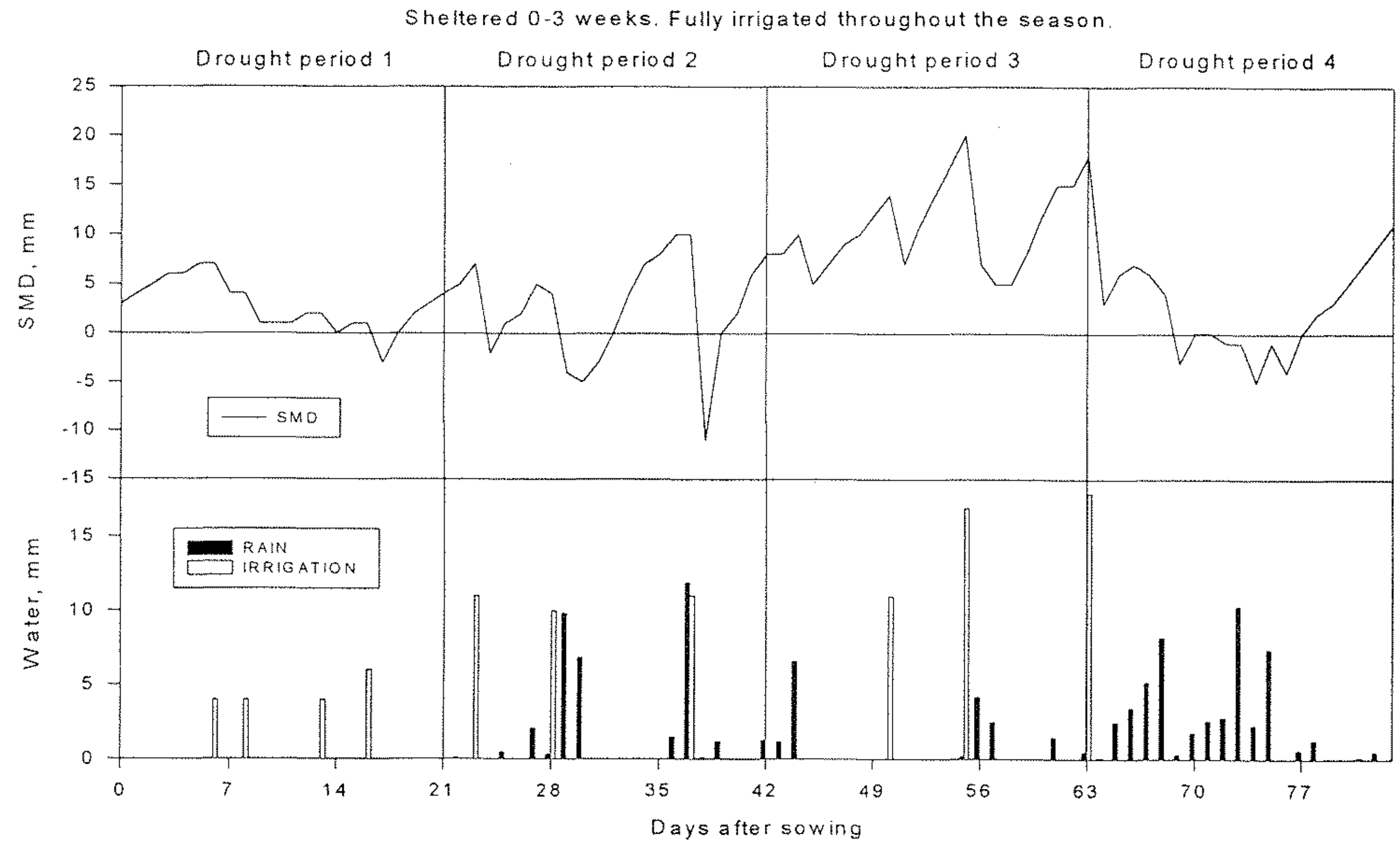

Sheltered 0-3 weeks. Fully irrigated throughout the season.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
25
20
15
10
5
0
-5
-10
-15
SMD
Water, mm
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 4

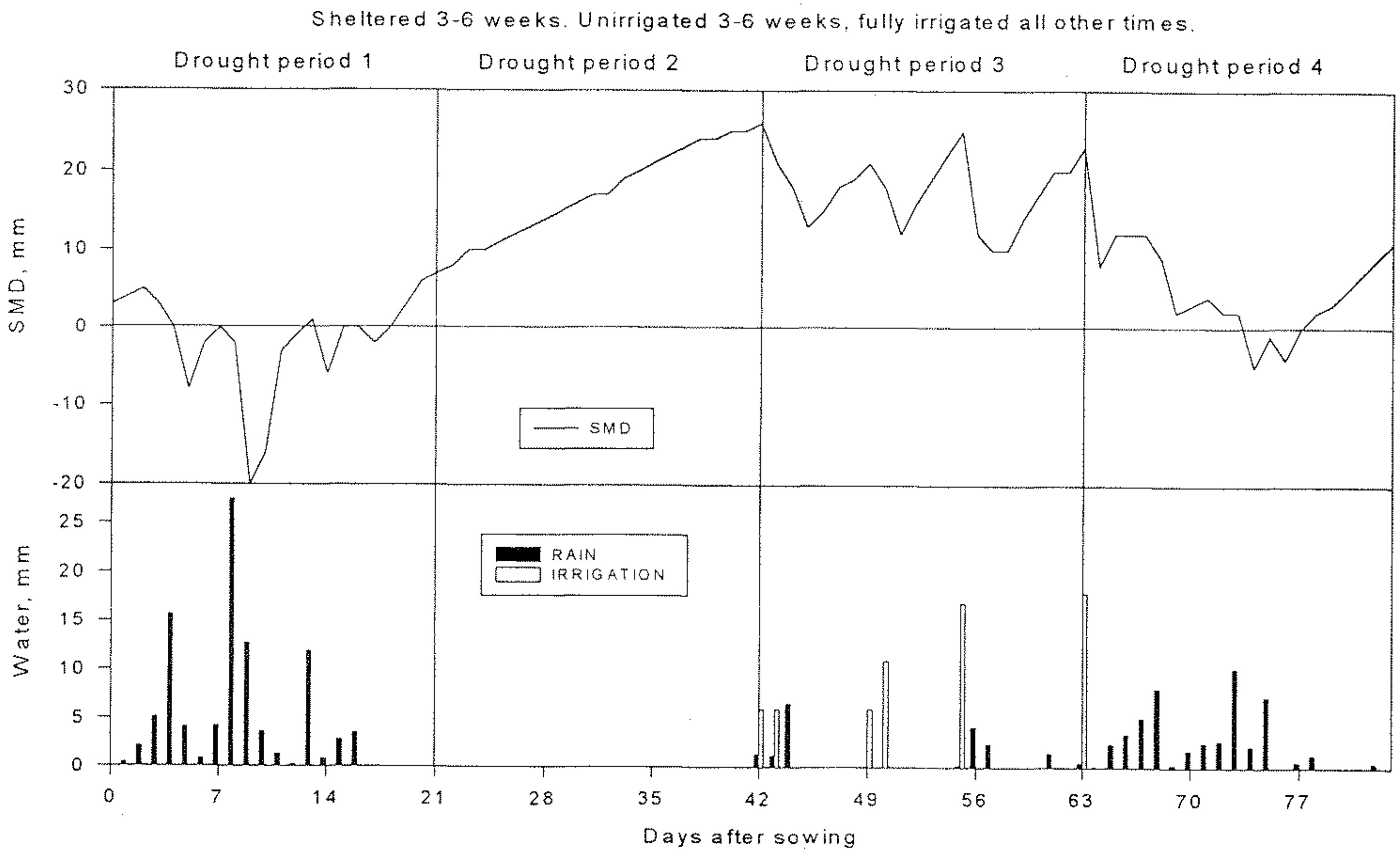

Sheltered 3-6 weeks. Unirrigated 3-6 weeks, fully irrigated all other times.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
30
20
10
0
-10
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 5

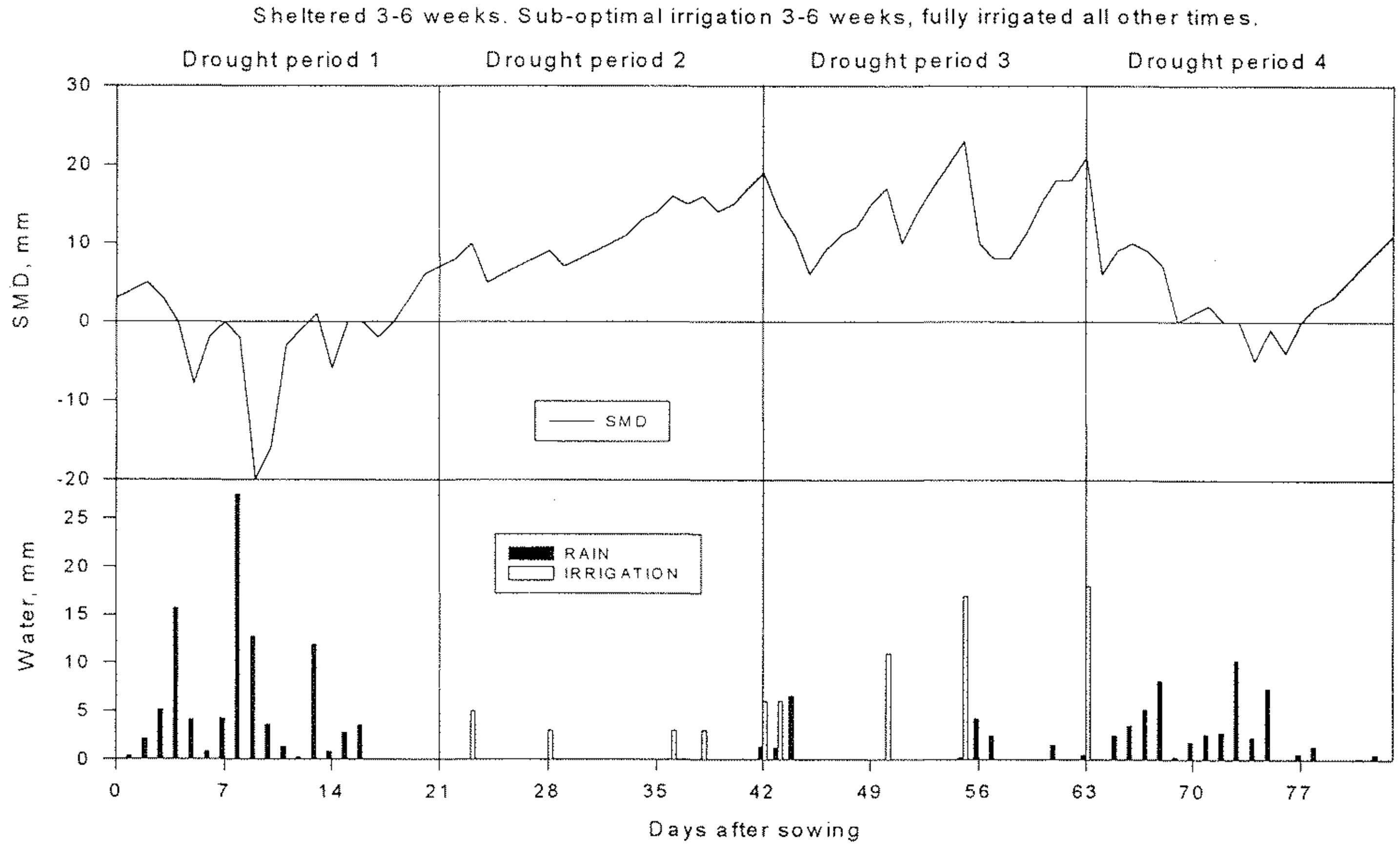

Sheltered 3-6 weeks. Sub-optimal irrigation 3-6 weeks, fully irrigated all other times.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
30
20
10
0
-10
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 6

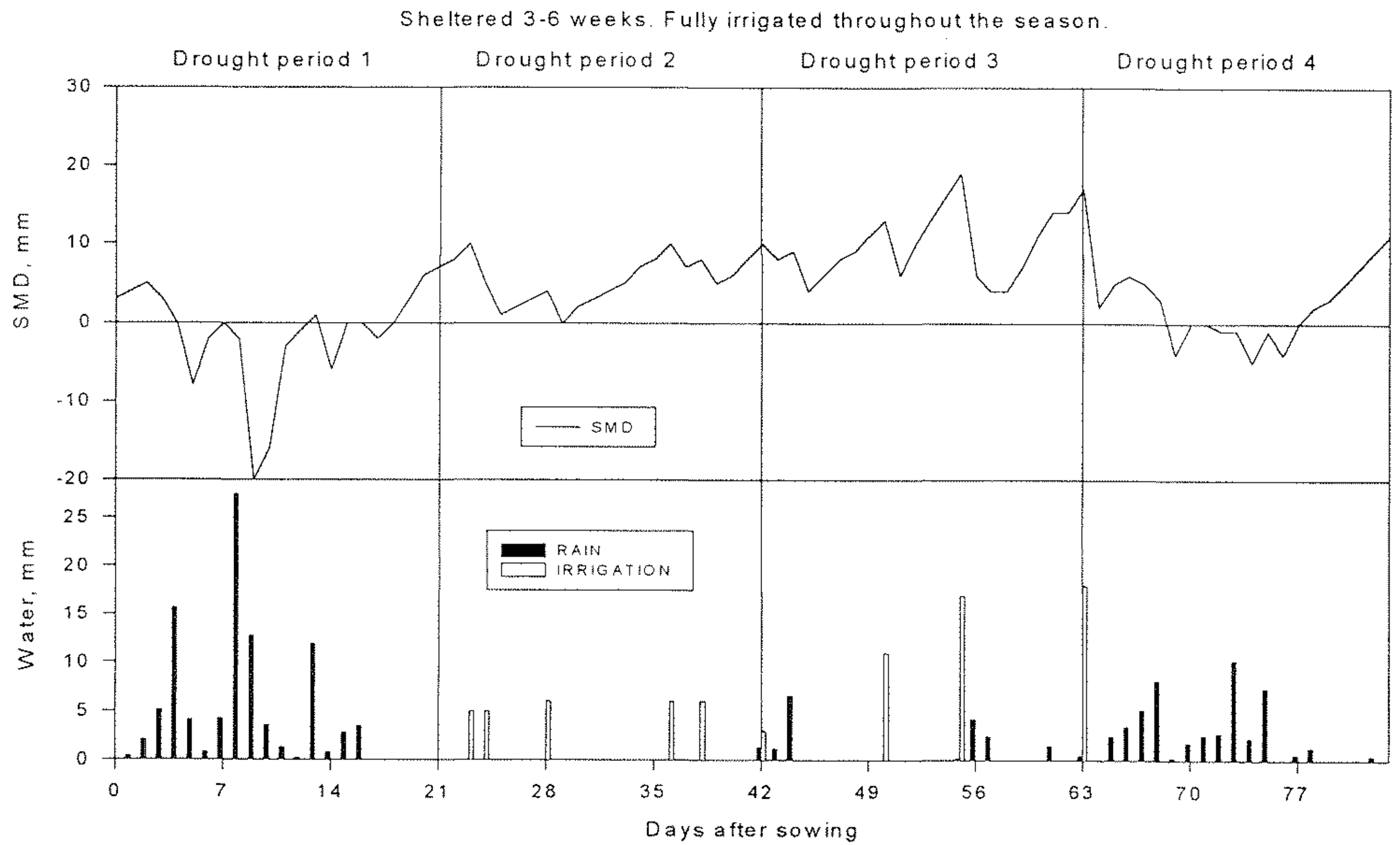

Sheltered 3-6 weeks. Fully irrigated throughout the season.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
30
20
10
0
-10
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 7

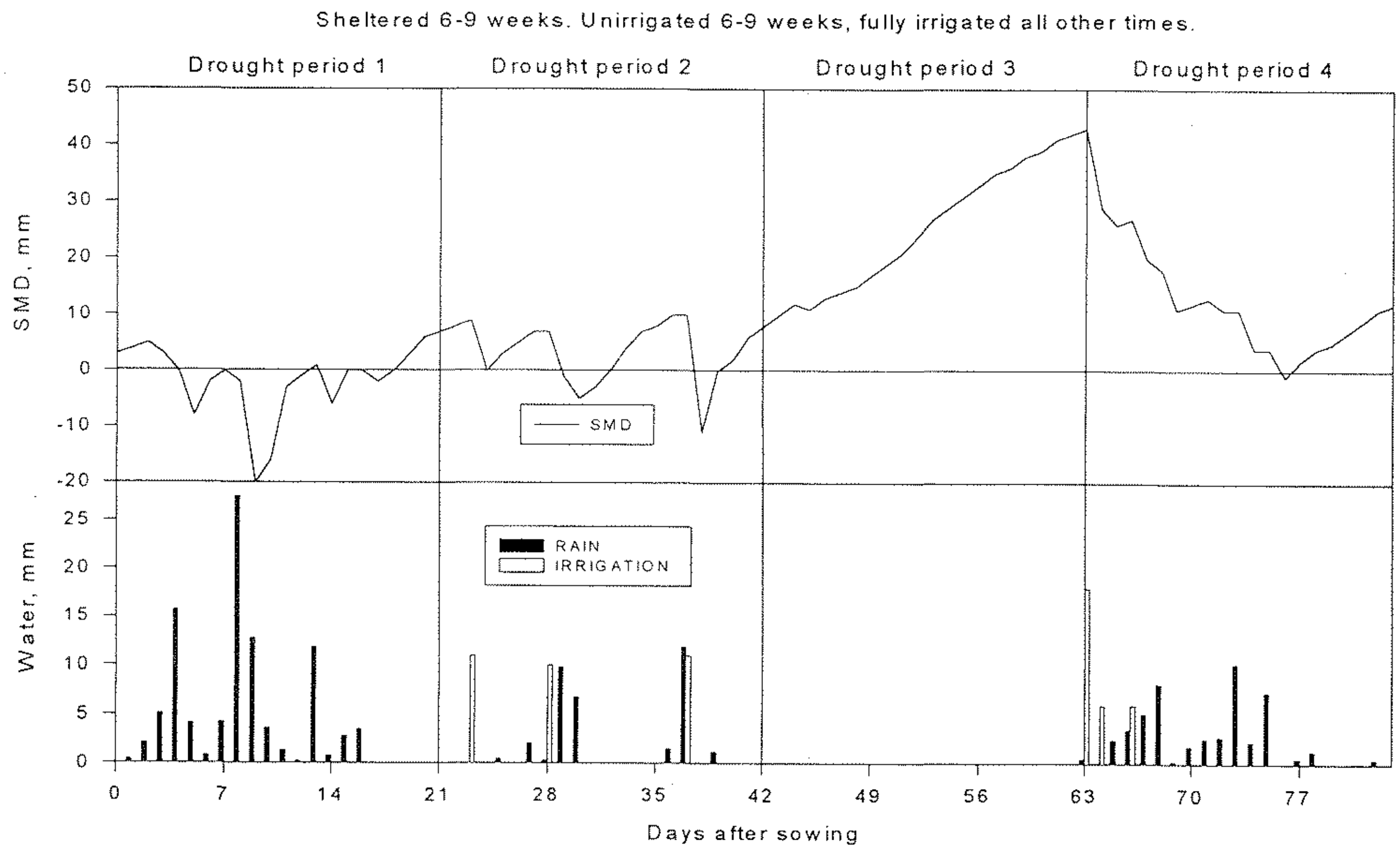

Sheltered 6-9 weeks. Unirrigated 6-9 weeks, fully irrigated all other times.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
50
40
30
20
10
0
-10
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 8

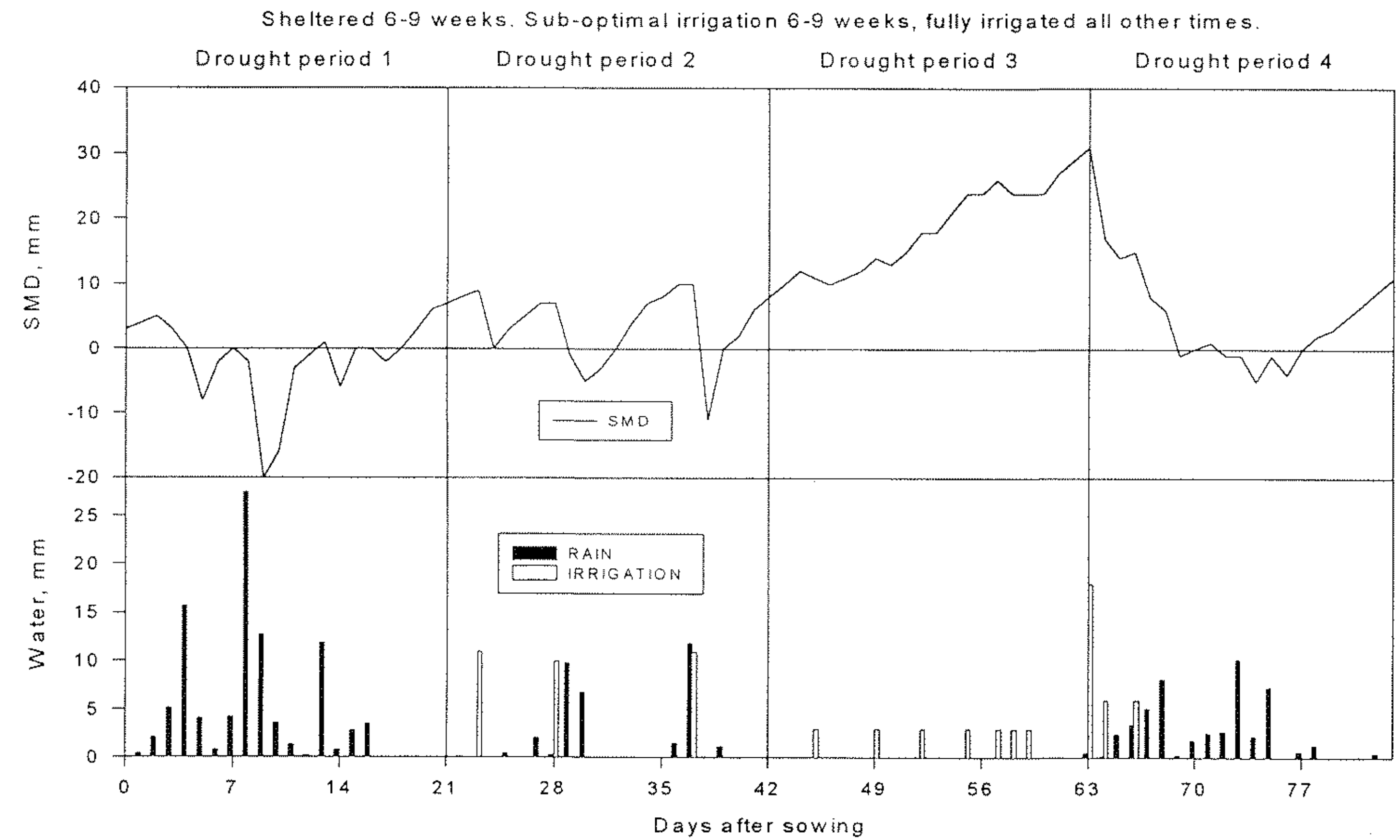

Sheltered 6-9 weeks. Sub-optimal irrigation 6-9 weeks, fully irrigated all other times.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
40
30
20
10
0
-10
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 9

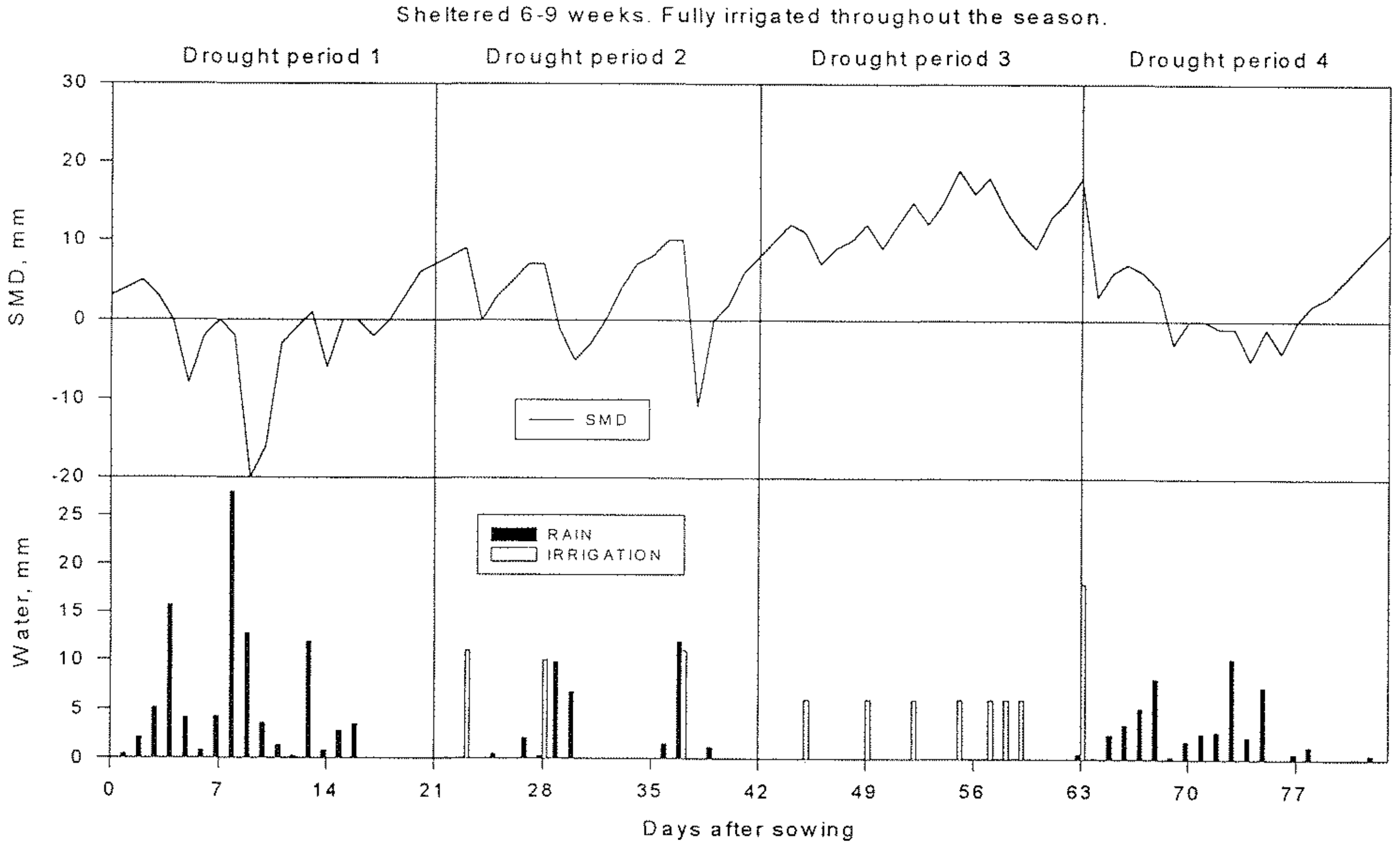

Sheltered 6-9 weeks. Fully irrigated throughout the season.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
30
20
10
0
-10
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 10

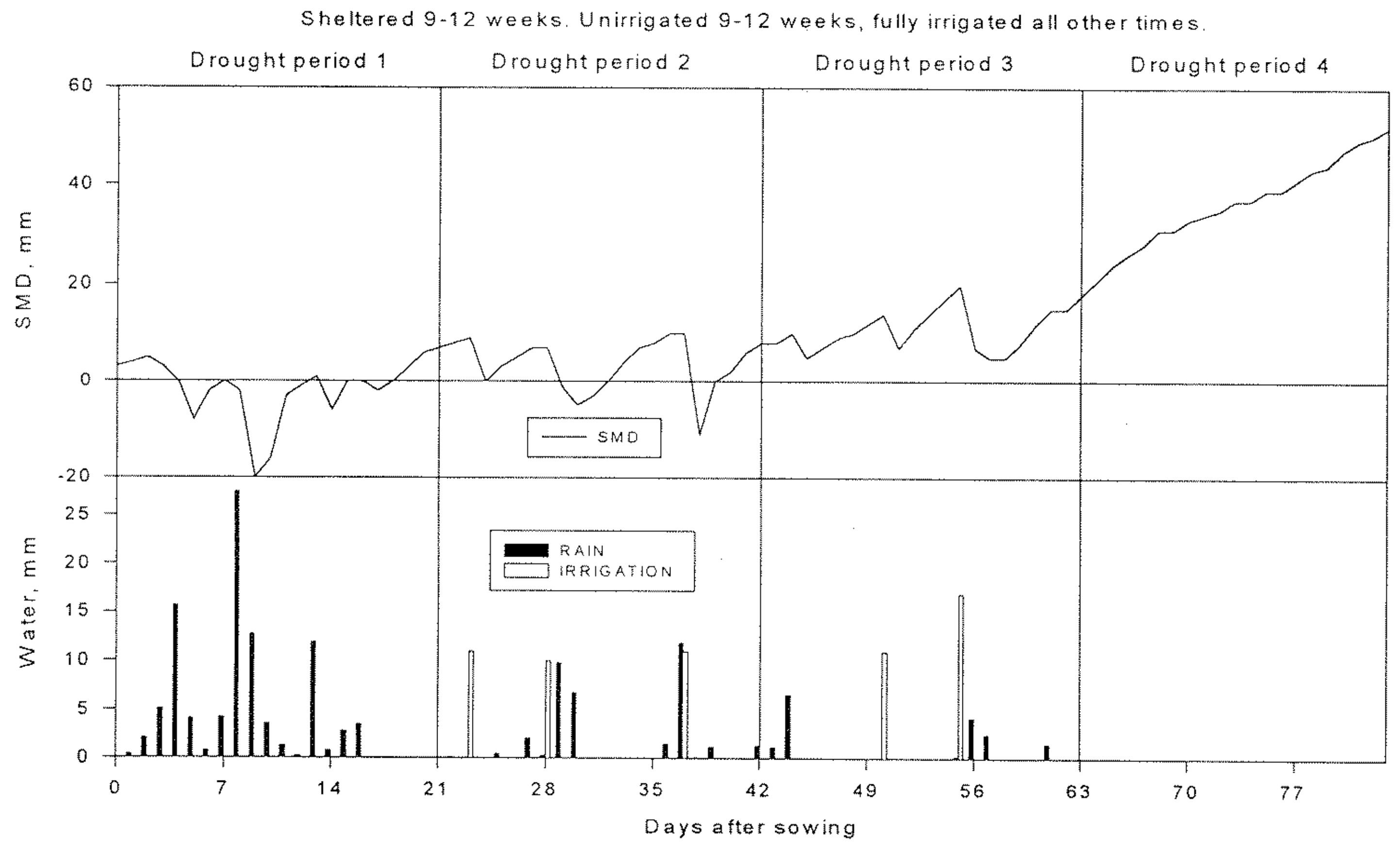

Sheltered 9-12 weeks. Unirrigated 9-12 weeks, fully irrigated all other times.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
60
40
20
0
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 11

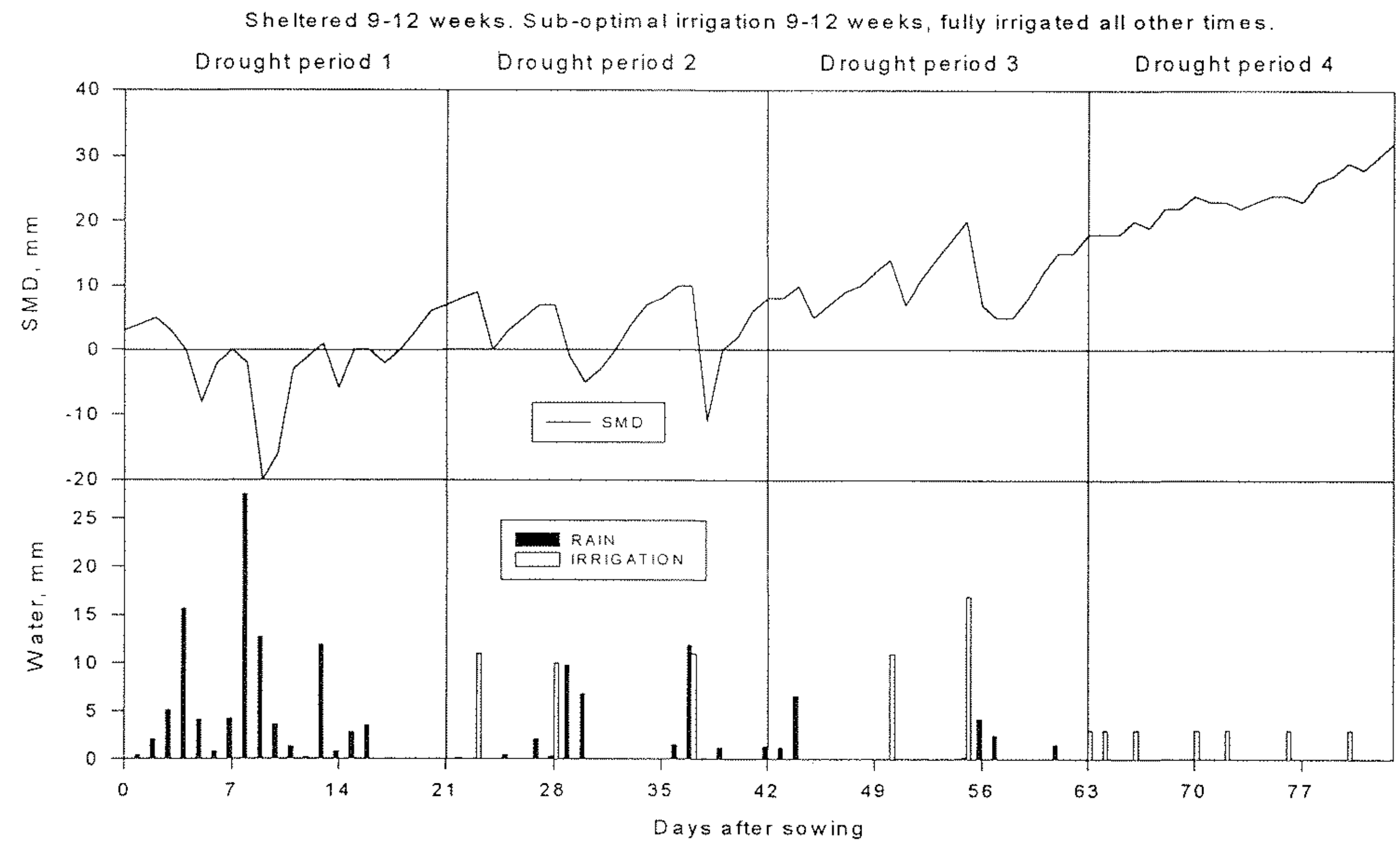
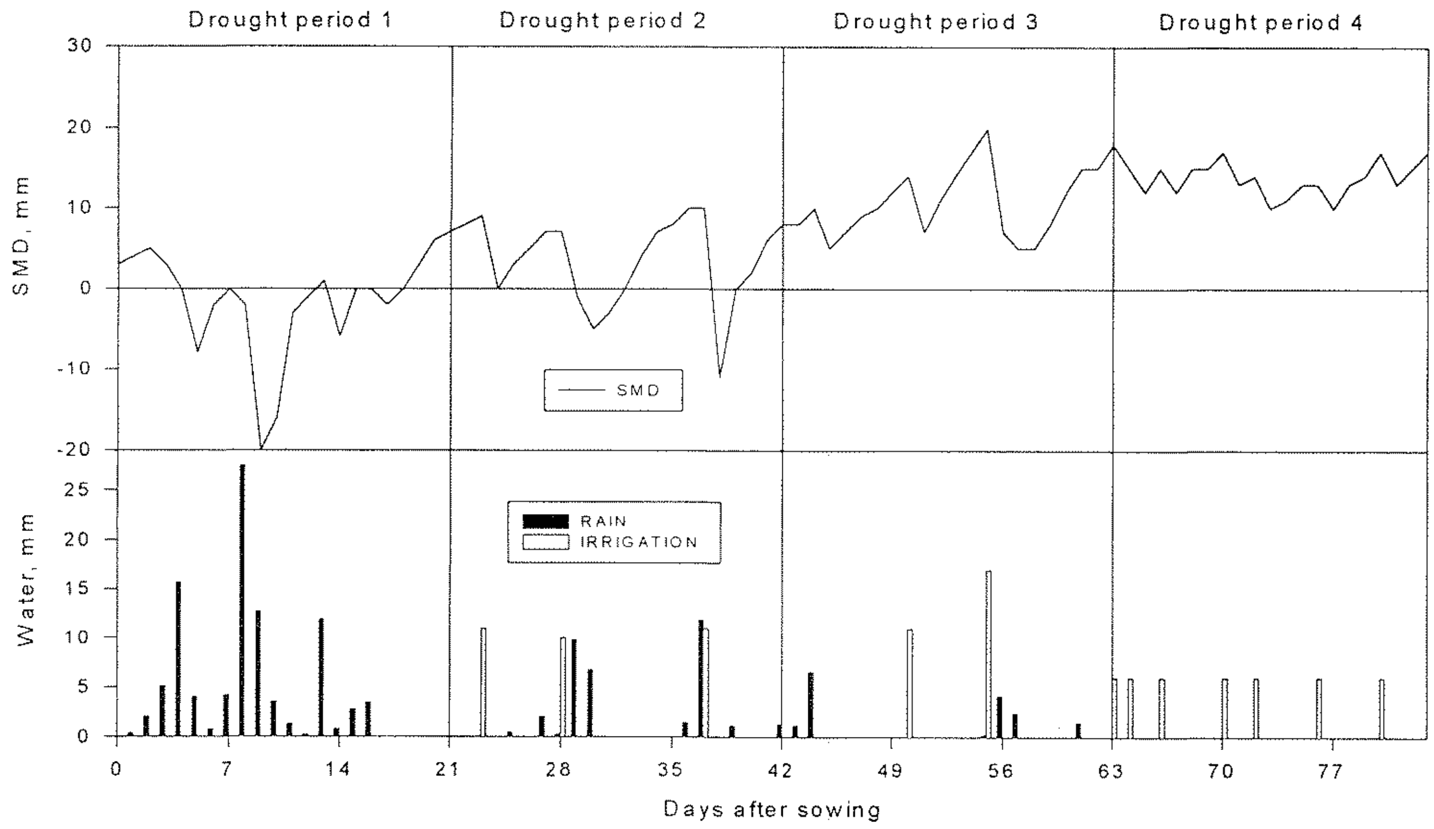

Sheltered 9-12 weeks. Sub-optimal irrigation 9-12 weeks, fully irrigated all other times.
Drought period 1
Drought period 2
Drought period 3
Drought period 4
SMD, mm
40
30
20
10
0
-10
-20
SMD
Water, mm
25
20
15
10
5
0
RAIN
IRRIGATION
0
7
14
21
28
35
42
49
56
63
70
77
Days after sowing

Figure 12

Sheltered 9-12 weeks. Fully irrigated throughout the season.



APPENDIX 3

Irrigation applications by date and amount

Shelter treatments	Irrigation treatments	Amount applied (mm)																	Total (mm)
		Date 23/06/97	25/06/97	30/06/97	03/07/97	08/07/97	09/07/97	10/07/97	15/07/97	24/07/97	06/08/97	11/08/97	19/08/97	15/09/97	26/09/97				
Shelter 0-3 weeks	Unirrigated	0	0	0	0	4	5	11	10	11	11	17	18	17	9				113
	Full irrigation	4	4	4	6	0	0	11	10	11	11	17	18	17	9				122
	Sub-optimal irrigation	2	2	2	3	0	0	11	10	11	11	17	18	17	9				113
		Date 10/07/97	11/07/97	15/07/97	23/07/97	25/07/97	29/07/97	30/07/97	05/08/97	06/08/97	11/08/97	19/08/97	15/09/97	26/09/97					
Shelter 3-6 weeks	Unirrigated	0	0	0	0	0	6	6	6	11	17	18	17	9					90
	Full irrigation	5	5	6	6	6	3	0	0	11	17	18	17	9					103
	Sub-optimal irrigation	5	0	3	3	3	6	6	0	11	17	18	17	9					98
		Date 10/07/97	15/07/97	24/07/97	01/08/97	05/08/97	08/08/97	11/08/97	13/08/97	14/08/97	15/08/97	19/08/97	20/08/97	22/08/97	15/09/97	26/09/97			
Shelter 6-9 weeks	Unirrigated	11	10	11	0	0	0	0	0	0	0	18	6	6	17	9			88
	Full irrigation	11	10	11	6	6	6	6	6	6	6	18	0	0	17	9			118
	Sub-optimal irrigation	11	10	11	3	3	3	3	3	3	3	18	6	6	17	9			109
		Date 10/07/97	15/07/97	24/07/97	06/08/97	11/08/97	19/08/97	20/08/97	22/08/97	26/08/97	28/08/97	01/09/97	05/09/97	08/09/97	11/09/97	15/09/97	17/09/97	26/09/97	
Shelter 9-12 weeks	Unirrigated	11	10	11	11	17	0	0	0	0	0	0	0	10	6	21	15	9	121
	Full irrigation	11	10	11	11	17	6	6	6	6	6	6	6	10	0	21	15	9	157
	Sub-optimal irrigation	11	10	11	11	17	3	3	3	3	3	3	3	10	6	21	15	9	142

APPENDIX 5

SCHEDULE FOR
FV 195
(Revised Version)

1. BACKGROUND AND COMMERCIAL OBJECTIVE

It has been documented from research work conducted at ADAS Gleadthorpe that the incidence of common scab in potatoes can be reduced by the appropriate management of soil moisture (Lapwood et al, 1973). Irrigation is now widely used to control the disease in potatoes by the application of water during the first 6 weeks of tuber initiation (Bailey, 1990). The causal organism of carrot scab is similar to that of potatoes (*Streptomyces scabies*) and may be controlled by the same technique. Published work from ADAS Gleadthorpe has established a relationship between watering regime and the incidence of carrot scab (Groves & Bailey, 1994). The results of this work suggest that low levels of soil moisture at particular times of the season may be crucial to the development of the disease. However, the experiments with carrots were designed to investigate the effect of irrigation on yield and therefore did not address the issue of scab control.

The work proposed here seeks to build on this earlier work by developing a disease control strategy which identifies the period of plant growth most sensitive to disease development and describing the conditions associated with pathogen infection. The experiment will be conducted at ADAS Gleadthorpe under the centre's automatic rain shelters thus ensuring complete management of the soil moisture status without the risk of interference from rainfall.

The commercial objective of this work will be to devise an irrigation strategy for the control of carrot common scab.

2. POTENTIAL FINANCIAL BENEFIT TO THE INDUSTRY

In the harvest year 1995/96 common scab was a widespread problem in crops grown on light soils. The lost profit from many such crops was as much as £50/t equating to a loss of approximately £5,000/ha for a 100t/ha crop. The cost of irrigating such crops to control scab would be in the region of 150 to £250/ha indicting a clear financial benefit provided adequate control can be achieved.

3. SCIENTIFIC AND TECHNICAL TARGET OF THE WORK

The scientific objectives of the work are as follows:

a. Determine the crop growth stage particularly associated with pathogen infection.

b. Determine the soil moisture conditions associated with pathogen infection.

c. Develop a commercial irrigation schedule for disease control.

4. CLOSELY RELATED WORK - COMPLETED OR IN PROGRESS

There has been considerable work studying the control of scab in potatoes mostly conducted during the sixties and seventies by staff in ADAS and at Rothamstead. Very little work has been done on scab in other crops apart from a single paper detailing a failure to control the disease in red beet with irrigation (Lapwood et al, 1976). As regards carrot scab a recent literature search in 1994 revealed previous reports of the control of scab with irrigation. The only recently published work on this subject is that detailed earlier (Groves & Bailey, 1994) which resulted from work funded by MAFF on increasing carrot yields with irrigation.

5. DESCRIPTION OF THE WORK

Experimental plots will be sited under an automatic rain shelter facility on ground where severe carrot scab has been recorded in the past.

YEAR 1: (1997)

Timing evaluation

Previous work together with grower experience suggests that the timing of irrigation is likely to be crucial. The first year of the experiment will therefore seek to identify the crop growth stage most sensitive to infection.

Plots will be sown with carrots under automatic rain shelters in May. Periods of drought will then be imposed as described below. A randomised split plot experimental design will be used with four replicates of each main treatment. Main plot size will be 12 by 5m (60m^2).

Main treatment list

1. Droughted for 21 days after sowing, but fully irrigated for the rest of the season.

2. Irrigated for 21 days after sowing, then droughted for 21 days, then fully irrigated for the rest of the season.

3. Irrigated for 42 days after sowing, then droughted for 21 days, then fully irrigated for the rest of the season.

4. Irrigated for 63 days after sowing, then droughted for 21 days, then fully irrigated for the rest of the season.

Appendix 5 - Contract of work schedule

Each main treatment plot will be split into a further 3 sub-plots ($10m^2$) to provide 48 plots (12 treatments x 4 replicates) in all. Sub-plot irrigation treatments will be applied during the periods of drought as described below:

Sub-treatment list

1. Unirrigated.

2. Irrigated with half the amount applied to sub-treatment 3.

3. Fully irrigated.

Full irrigation will seek to maintain the SMD close to field capacity i.e. <15mm early in the season, <25mm after 7 true leaf stage. The computer program, Irriguide, will be used to schedule irrigation in conjunction with gravimetric measurements of soil moisture (see below). Plots will be harvested in September/October.

Observations and measurements:

1. Soil moisture status: Soil moisture status will be measured gravimetrically in plots at the start, during and at the end of each drought period. Soil samples will be taken from the area immediately adjacent to the tap roots for these soil moisture measurements. Due to the limited plot size soil moisture will be measured less frequently during periods when drought is not being imposed.

2. Disease incidence at harvest: Root yield will be measured in all plots. A sub-sample of 75 roots will be taken from the total yield of each plot and scored for % surface area affected with common scab using the NIAB assessment keys. The mean incidence and mean percentage surface area affected will then be calculated. Additionally, the produce will be assessed for the incidence of root fanging and root cracking.

YEAR 2 (1998)

Irrigation Timing

The first year results did not identify growth stages particularly sensitive to disease infection. This work will therefore be repeated.

Seed will be sown during May into a loamy sand soil under the rain shelter facility. The target plant population will be 1 million plants per hectare. Irrigation will be applied according to treatment using the linear move irrigator. Appropriate agrochemicals and fertilisers will be applied to ensure optimum growth. Periods of drought will be imposed as below from May to August/September.

Soil moisture surrounding the tap root will be measured at emergence and at the end of each drought period. Crop cover assessments will be conducted on sufficient occasions to enable accurate irrigation scheduling.

The plots will be hand harvested approximately 20 weeks after sowing. The yield and number of topped roots from the centre two rows of each plot will be measured. A sub-sampled of 100 roots will be taken from the yield sample for disease assessments. The roots will be washed and assessed for common scab using the appropriate NIAB key. The number of roots with cracks of fanging will also be recorded.

Treatments

1. Droughted for 4 weeks immediately after emergence but fully irrigated at all other times.
2. Droughted from the start of week 5 until the end of week 8 after emergence but fully irrigated at all other times.
3. Droughted from the start of week 9 to the end of week 12 after emergence but fully irrigated at all other times.
4. Droughted from the start of week 13 to the end of week 16 after emergence but fully irrigated at all other times.

Full irrigation will seek to maintain the SMD close to field capacity i.e. more than 12mm up to week 8 and less than 20mm thereafter. The computer program Irriguide will be used to schedule irrigation.

Experiment design

Randomised block design with four replicates of each treatment. Data will be analysed by analysis of variance. Each plot will be split in half with one half set aside for harvest and disease assessment and the other for sampling.

Plot size

Two beds 3.46m x 10m (34.6m^2).

Irrigation frequency

The results from 1997 suggest that frequency of irrigation affects the soil surface moisture which in turn affects scab development. A series of pot tests will be conducted in year 1998 to test this hypothesis.

Thirty 20cm plant pots will be filled with loamy sand soil taken from the field site. Six seeds will be planted in each pot and watered in. Upon germination the seedlings will be thinned out to 4 per pot. Watering treatments will be applied for 16 weeks.

Soil water content will be measured in each pot at monthly intervals just before water is applied to each treatment, i.e. at the point of maximum soil moisture deficit.

After 16 weeks each pot will be emptied, roots washed and the incidence of scab recorded.

Treatments

1. Watered to saturation every 2 days.

2. Watered to saturation every 4 days.

3. Watered to saturation every 6 days.

4. Watered to saturation every 8 days.

5. Watered to saturation every 10 days.

Experiment design

Randomised block design with 6 replicates of each treatment. Data will be analysed by ANOVA.

The level of soil moisture required to control common scab

Soil moisture will be regularly recorded in both the experiments described above from May to August/September. This information, together with that already collected in 1997, should provide the basis for the development of a commercial irrigation strategy.

6. LOCATION

ADAS Gleadthorpe, Meden Vale, Mansfield, Nottinghamshire, NG20 9PF.

7. STAFF RESPONSIBILITIES

Project Leader:	Mr Simon J Groves, ADAS Gleadthorpe, Meden Vale, Mansfield, Nottinghamhire, NG20 9PF. Tel: 01623 844331 Fax: 01623 844472
Project Co-ordinator:	Mr Paul Knights, W.H. Knights and Sons, Crow Hall Farm, Gooderstone, Kings Lynn, Norfolk, PE33 9DA

8. COSTS

First year	=	£12,970
Second year	=	£13,360
Total	=	£26,330

REFERENCES

ADAMS, M.J. & LAPWOOD, D.H. (1978). Studies on the lenticel development, surface microflora and infection by common scab (*Streptomyces scabies*) of potato tubers growing in wet and dry soils. *Annals of Applied Biology*, **90**, pp 335-343.

BAILEY, R.J. (1990). Irrigated Crops and their Management. *Farming Press* pp192.

GROVES, S.J. & BAILEY, R.J. (1994). The effect of irrigation upon the root yield and incidence of common scab of carrots. *Aspects of Applied Biology* **38** pp217-221.

LAPWOOD, D.H., ADAMS, M.J., CRISP, A.P. (1976). The susceptibility of red beet cultivars to *Streptomyces scabies*. Plant Pathology **25** pp.31-33.

LAPWOOD, D.H., WELLINGS, L.W. & HAWKINS, J.H. (1973). Irrigation as a practical means of controlling common scab (*Streptomyces scabies*). *Plant Pathology* **22** pp 35-41.

SØRENSEN, J.N, JØRGENSEN, U., KÜHN, B.F. (1997). Drought effects on the marketable and nutritional quality of carrots. *Journal of Science Food and Agriculture* **74** pp 379-391.

