Project title:	Impact of irrigation practices on Rijnsburger bulb onion husbandry, quality and storability - II
Project number:	FV 326a
Project leader:	Dr. Tim Lacey, Vegetable Consultancy Services (Developments) Ltd.
Report:	Final Report
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Key staff:	Dr Tim Lacey Dr Eric Ober
Location of project:	Broom's Barn Research Centre, Suffolk and RL Long Farms Ltd., Suffolk.
Industry Representative:	Tim Jolly, WO & PO Jolly Ltd., Roudham Farm, Roudham, East Harling, Norfolk NR16 2RJ
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DISCLAIMER

[The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.]

AUTHENTICATION

We declare that this work was carried out under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Dr. Tim Lacey
Research Agronomist
Vegetable Consultancy Services (Developments) Ltd.

Signature .... Date ....

Dr Eric Ober
Crop Physiologist
Booms Barn Research Centre

Signature .... Date ....

Report authorised by:

[Name]
[Position]
[Organisation]

Signature .... Date ....

[Name]
[Position]
[Organisation]

Signature .... Date ....

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The authors would like to acknowledge the invaluable assistance of RL Long Farms Ltd. in accommodating the open-field trial within their commercial onion land. Thanks also to Wroot Water and Pessl Instruments for their assistance in the technical aspects of trial operation.

GROWER SUMMARY

Headline

This project provides best practice guidelines for optimising bulb onion irrigation

Background

An estimated 85% of dry bulb onion crops in the UK are irrigated, following a drive in the industry for production on light soils to improve quality and aid crop management. However, there are concerns that existing irrigation practices may be compromising crop yield, quality and storability. Furthermore, there is little scientific evidence to support current practices, either for crop production or to justify irrigation water use and demonstrate efficiency for abstraction licence renewal in the future.

This project builds on findings from a 1-year HDC trial FV 326 (2007-8), which strongly indicated that irrigation practices had a significant impact on crop performance. However, due to inherent limitations of FV 326, further, large-scale field-based trials were required to fully evaluate the impact of irrigation regimes, particularly on crop quality and storability. This follow-on project proposes to address these issues by extending the original study to one commercial-scale field trial plus one rain-shelter trial over a period of 3 seasons.

Ultimately, this project will lead to the identification of optimum irrigation practices in the form of best-practice guidelines to help growers maximise marketable percentages and increase the storage period of bulb onions. Furthermore, the findings will assist growers at abstraction licence renewal and may show benefits for nutrient and weed management.

This report summarises the data from all 3 years of the trial. For specific data relating to individual years, please refer to the respective Annual Reports.

Summary

- Water stress up to egg-stage significantly reduces onion yields and profitability.
- Little and often irrigation from bulb initiation to egg-stage is worth prioritising to increase yield and size, unless the forecast is unsettled.
- Early or late season little and often irrigation may increase yields, but caution is advised to balance against risks.

A range of irrigation regimes, applied using over-head sprinklers, were tested during the 3 year project, both under rain-shelters and at an open-field commercial site. Irrigation treatments were based on combinations of different quantities and frequency of irrigation (see Table 1), applied during different stages of crop development:

- Early-season – from 2-3 true leaves (approx. mid May) to bulb initiation (approx. early July)
- Mid-season – from bulb initiation to egg-stage (approx. early August)
- Late-season – from egg-stage until irrigation stop timing
- Stop timing – at 50% or 100% canopy fall-over

Table 1 Irrigation practices used to determine irrigation regimes

Irrigation practice	Code	Typical trigger for irrigation*	Typical application depth*	Typical application interval**	Comment
Typical	T	~50% AWC used up	25mm	7-10 days	Standard practice for most onion growers during the main part of the season.
Little and often	L	~25% AWC used up	15mm	3-5 days	Effectively half as much twice as often, but note that the application depth is higher to account for evaporative losses at each event.
Stress	S	~75% AWC used up	25mm	10-14 days	This regime should maintain a soil moisture deficit – i.e. not return the soil to field capacity when irrigated. This is usually used during "Late" season to encourage uniform bulbing and maturity.
Excess (2010 only)	X	~12.5% AWC used up	10mm	2-3 days	In effect, this regime keeps the soil as wet as practically possible to achieve.
No Irrigation (2010 only)	N	-	-	-	Zero irrigation after wetting to field capacity at the start of the season.

*Assuming typical loamy sand or sandy loam soil, with rooting zone of 300mm
**Assuming crop with rapidly growing or full canopy under typical June/July/August conditions (subject to rainfall)

AWC = Available water content

Crop growth was measured during the season and harvested bulb samples were cured and stored in a commercial onion store for assessment in May the following year for post-storage yield, size and quality. The effect of the irrigation treatments on foliar pests and diseases, weed flushes and nitrate leaching were also monitored through the season. The

data was analysed to help identify optimal irrigation practices for bulb onion production, with the ultimate aim of producing a "best-practice" fact-sheet.

Overall, the results indicated that "little and often" irrigation applied during early season (to bulb initiation), and particularly during mid-season (from initiation to "egg" stage) significantly increased crop development and reduced thrip damage when compared to "typical" irrigation. However, although such practices led to some yield and bulb diameter increases, these were not always significant when compared to "typical" irrigation.

Late season irrigation after "egg" stage until irrigation stop (usually at 50% fall-over) and irrigation beyond 50% fall-over also significantly increased bulb yield and size compared to the normal practice of inducing stress during the late season and stopping at 50% fall-over.

However, the potential yield benefits of both "little and often" and late season irrigation need to be carefully balanced against the additional risks these practices pose. There was evidence that more frequent irrigation early in the season could increase weed levels and the risk of bolting where excess foliage development occurs. More frequent irrigation during the late season period increased foliar disease levels (especially downy mildew), delayed canopy fall-over and reduced bulb dry matter content. Furthermore, late irrigation could potentially jeopardise harvesting operations if further rainfall is received.

The project also showed that irrigation practices which maintain a level of water stress during the season were detrimental to crop production – with the period up to bulb initiation highlighted as critical. There were also indications that water stress may cause increased bulb diseases, internal disorders and perhaps also greater re-growth during storage.

Cost-benefit analysis and recommended irrigation practices are given below.

Financial Benefits

Onion production costs and gross returns for all the irrigation regimes tested were calculated using the assumptions in

Table 2 and Table 3.

Table 2 Irrigation costs assumed for cost-benefit analysis based on grower estimates and published figures

Element	Cost	Comment
Typical 25mm irrigation	£120 */ ha per irrigation*	Typically £85-£150, based on grower estimates and published figures
Of which "event" cost	£22.50 */ ha per irrigation*	Labour and tractor costs to move equipment
Of which water charge/pump	£32.50 */ ha per irrigation*	Volume-based EA abstraction charge and pumping costs, equivalent to £1.30 /mm/ha
Therefore typical "fixed" costs	£65.00 */ ha per irrigation*	Capital costs (infrastructure, equipment, maintenance etc)
Annual "fixed" costs	£390 */ha per annum*	Assuming 150mm per annum applied (i.e. 6x 25mm applications)
Calculated costs for:		
Typical 25mm irrigation	**£55 */ha per irrigation event***	**Plus annual fixed costs of £390 /ha**
Little and often 15mm irrigation	**£42 */ha per irrigation event***	**Plus annual fixed costs of £390 /ha**
Excess 10mm irrigation	**£35.50 */ha per irrigation event***	**Plus annual fixed costs of £390 /ha**

Table 3 Assumed farm-gate brown onion prices by size grade

Size grade	Price	Comment
<45mm	£25 / tonne	40-60mm price = £100/tonne. It is assumed that a small proportion of <45mm onions would fit in the 40-45mm size range and so achieve this estimated value per tonne.
45-60mm	£100 / tonne	
60-80mm	£250 / tonne	Range £240-260
80-90mm	£200 / tonne	Processing market – typically volatile prices
>90mm	£50 / tonne	Little market for over-size

Cost-benefit analysis reflected trial data, indicating that even relatively low stress conditions through the season could reduce profitability compared to "typical" practice by up to 150% in dry conditions. The analysis also suggested that "little and often" irrigation would be considerably more profitable by at least 50% in drier seasons when compared to "typical" practice, but less profitable by up to 17% in wetter seasons. Furthermore, the analysis indicated that late season irrigations could increase profitability by around 50%, particularly under dry conditions. However, these analyses did not take into account the additional risk posed by such practices which were highlighted earlier (e.g. potentially increased bolting, greater foliar disease and weed levels, delayed crop maturity and lower bulb dry matter).

Further analysis demonstrated that crop yields correlated strongly with total irrigation + rainfall up to a threshold of around 270mm total water applied during the period from 2-3 true leaves (approx. mid May) until harvest (Figure 1). This threshold level is likely to be higher in years with more solar radiation (i.e. less cloud cover) and consequently greater crop growth potential.

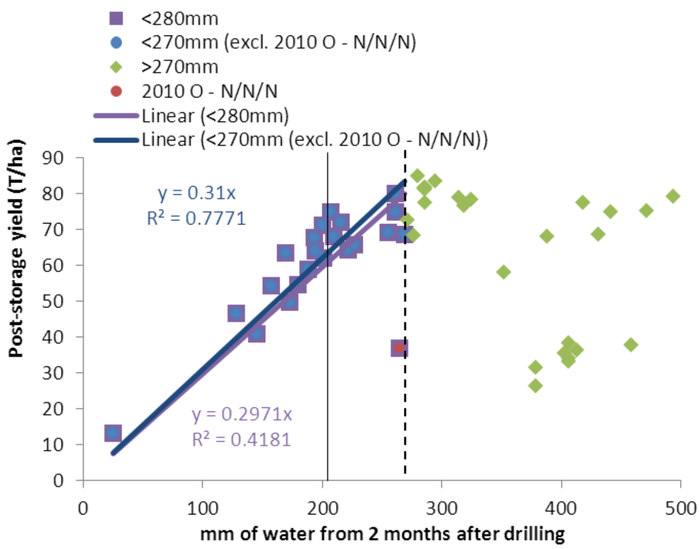


Figure 1 Correlation between total water received and crop yield. Solid line indicates mean East Anglia rainfall May-Aug (inclusive) 1970-2012. Dashed line indicates threshold level.

This analysis suggested that the average yield under rain-fed production (with no irrigation) was around 20 T/ha less than that achievable under irrigated production – equating to an average reduction in gross returns of around £3,400 (or higher if the effect on bulb size is taken into account). With production costs typically around £3,250 (plus irrigation and storage/grading costs), this highlights the critical importance of optimised irrigation to the industry.

Action Points

Based on the trial results and the cost-benefit analysis above, the irrigation practices in Table 4 are suggested as a reasonable and practical balance between achieving optimum crop yield and quality while minimising agronomic and financial risk.

Note that Table 12 has been generated with the assumption that weather conditions are predicted to remain dry for a period after irrigation has commenced. Consideration of forecast rain should always be given when programming irrigation in order to minimise the risks of drainage (and wasted irrigation effort/cost) by irrigating soil to field capacity when wet conditions are imminently forecast. Adjustments to application depths could be made to account for predicted rainfall if required.

“Best practice” guidelines, based on the recommendations from this project will be summarised in an industry facsheet, to be published by the HDC following this report.

Table 4 Suggested optimum irrigation regime for bulb onions (for sandy loam / loamy sand). Note that suggested applications are subject to individual soil characteristics and consideration should be given to forecast rain before scheduling applications.

Crop growth stage	ESTABLISHMENT Drilling to 2-3TL			EARLY SEASON 2-3TL to bulb initiation			MID SEASON Initiation to "egg" stage			LATE SEASON "Egg" stage to stop			STOP TIME		
Comment	If sufficient moisture in seed bed, irrigation only required under very dry conditions to aid establishment and pre-emergence herbicide activity.			Early season irrigation is important, becoming critical during particularly dry periods.			Mid season irrigation is critical to build crop biomass and promote bulb growth, becoming less important only under wet conditions.			During late season, controlled moisture stress should be allowed to develop to help promote bulbing and crop maturity. In particularly dry periods, more frequent irrigation will increase yields.			Under most circumstances, stop irrigation at 50% canopy fall-over. In particularly dry periods, irrigation up to 100% fall over will increase yields but should limit associated disease and quality risks.		
Weather	Dry	Normal	Wet	Dry	Normal	Wet	Dry	Normal	Wet	Dry	Normal	Wet	Dry	Normal	Wet
Importance of irrigation during period	Medium	Low	Low	High	Medium	Medium	High	High	Medium	Medium	Low	Low	Low	Low	Low
Description of irrigation trigger point and application	Low dose to minimise capping and cool shock potential.	Unlikely to be required	Not required	Return soil to FC when SMD reaches 25% of AWC	Return soil to FC when SMD reaches 50% of AWC	Return soil to FC when SMD reaches 50% of AWC	Return soil to FC when SMD reaches 25% of AWC	Return soil to FC when SMD reaches 25% of AWC	Return soil to FC when SMD reaches 50% of AWC	Return soil to FC when SMD reaches 50% of AWC	Apply approx. 50% of AWC when SMD reaches 75% of AWC	Apply approx. 50% of AWC when SMD reaches 75% of AWC	Stop at **50%** fall-over In extremes, further irrigation could be applied.	Stop at **50%** fall-over	Stop at **50%** fall-over
Estimated application for: Loamy sand (~35mm root zone AWC)	<10mm	-	-	12mm at 10mm SMD	20mm at 18mm SMD	20mm at 18mm SMD	12mm at 10mm SMD	12mm at 10mm SMD	20mm at 18mm SMD	20mm at 18mm SMD	20mm at 26mm SMD	20mm at 26mm SMD	20mm at 26mm SMD	-	-
Estimated application for: Sandy loam (~45mm root zone AWC)	<15mm	-	-	15mm at 12mm SMD	25mm at 23mm SMD	25mm at 23mm SMD	15mm at 12mm SMD	15mm at 12mm SMD	25mm at 23mm SMD	25mm at 23mm SMD	25mm at 34mm SMD	25mm at 34mm SMD	25mm at 34mm SMD	-	-

Green text indicates "little and often" practice; Blue indicates "typical" practice, Orange indicates "stress" regimes
FC = Field Capacity; SMD = Soil Moisture Deficit; AWC = Available Water Content

SCIENCE SECTION

Introduction

Cured and stored Rijnsburger dry bulb onions (*Allium cepa*) form a significant proportion of the UK vegetable sector. An estimated 85% of the crop is irrigated.

There are concerns that existing irrigation practices may be compromising crop yield, quality and storability. Furthermore, there is little scientific evidence to support current practices, either with respect to agronomic aims or to justify irrigation water use and demonstrate efficiency for abstraction licence renewal in the future.

To this end, project FV 326a was established to continue the successful FV 326 onion irrigation trial of 2007/8. FV 326 was a 1-year trial that demonstrated significant differences in crop production resulting from differing irrigation regimes under rain-shelter conditions. However, due to inherent limitations, further, large-scale field-based trials were required to fully evaluate the impact of irrigation regimes, particularly on crop quality and storability. This follow-on project addresses these issues by extending the original study to one commercial-scale field trial plus one rain-shelter trial over a period of 3 seasons.

Project FV 326a proposed to investigate a range of irrigation regimes (based on FV 326 and industry consultation) for their impact on bulb onion crop growth, yield, quality and storability and for the secondary impacts on nitrate leaching and weed flushes. Ultimately, the trial results have been used to identify optimum irrigation practices in the form of “best-practice” guidelines to help growers maximise marketable percentages and increase the storage period of bulb onions, thereby increasing profitability. Furthermore, the findings will assist growers at abstraction licence renewal and may potentially assist nutrient and weed management strategies.

This report summarises the data from all 3 years (2010, 2011 and 2012). For more specific analysis of data from individual years, please refer to the relevant annual reports.

Materials and methods

Experimental design and layout

The project comprised two parallel experiments in each year: at one site, a bulb onion crop was grown under artificial rain-shelters and exposed to a range of differing irrigation regimes; at a second location, the same irrigation regimes were applied on a site positioned within a commercial onion field. In all years, the rain-shelter site was hosted by Broom’s Barn Research Centre (near Bury St Edmunds, Suffolk) and the open-field site was hosted by RL & JP Long (also near Bury St Edmunds). Note that a different location was used each year at both the rain-shelter and the open-field site, following typical crop rotation practices. For the purposes of this report, the sites will be referred to as “rain-shelter” and “open-field” respectively, with a trial year (2010, 2011 or 2012) included as necessary. Details of each site are presented in Figure 2 and Table 5.

Figure 2 Field site locations 2012

Table 5 Details of rain-shelter and open-field sites

Year	Parameter	Rain-shelter	Open-field
All	Soil type	Sandy loam	Sandy loam
	Onion variety	Arthur	Arthur
	Target density	52 plants per m^2	48 plants per m^2
	Plot size	1 bed by 8m	3 beds by 10m
	No. of sprinklers per plot	8	16
	Replicates	3	3
	Crop husbandry	As field (except water)	As field (except water)
2010	Drilling date	18th March	10th March
	Wheel centres	2.03m	1.83m
	Date of wetting to field capacity (FC)	20th May	10th June
	Harvest date	15th September	18th September
2011	Drilling date	21st March	3rd March
	Wheel centres	1.83m	1.83m
	Date of wetting to field capacity (FC)	28th April	17th May
	Harvest date	30th August	14th September
2012	Drilling date	20th March	29th February
	Wheel centres	1.83m	1.83m
	Date of wetting to field capacity (FC)	13th May (rain only)	13th May (rain only)
	Harvest date	14th and 21st September	19th September

Each site had three replicate blocks of eight differing irrigation regimes, chosen based on results from FV 326 and industry advice. These were based around three key irrigation periods and differing irrigation practices during the season (Table 6 and Table 7). Treatments are listed in Table 8 for each year of the trial. Note that treatments were reviewed annually and revised, so some regimes differ from year to year.

Table 6 Key irrigation periods used to determine irrigation regimes

Key period	Crop stage	Approx. Timing	Comment
“Early” season	2-3 leaves *until* start of bulb initiation	Mid May *to* early July	This covers the early period of rapid canopy development.
“Mid” season	Start of bulb initiation *until* “egg” stage (elongated but strongly bulbing to around 30mm diameter)	Early July *to* early August	This covers the latter part of canopy development, including the resource partitioning change from leaf development to bulb development.
“Late” season	“Egg” stage *until* stop irrigation	Early August *to* mid-late August	Typically during this stage, soil moisture deficits are increased to induce controlled stress in the crop to help facilitate a uniform switch to bulb development. Field experience suggests that excess water during this stage (rain or irrigation) can cause a switch back to leaf production, inhibiting bulbing and potentially leading to bulbs with thick necks, tough leathery skins and therefore greater susceptibility to diseases during storage.
Stop irrigation	50% + fall-over	Mid-late August	Typically irrigation is halted when the crop has reached 50% fall-over. Field experience suggests that although additional green yield benefits are often observed by water applications after 50% fall-over, this can also cause greater susceptibility to diseases during storage

Table 7 Irrigation practices used to determine irrigation regimes

Irrigation practice	Code	Typical trigger for irrigation*	Typical application depth*	Typical application interval**	Comment
“Typical”	**T**	~50% AWC used up	25mm	7-10 days	Standard practice for most onion growers during the main part of the season.
“Less-more-often” (“L-M-O”)	**L**	~25% AWC used up	15mm	3-5 days	Effectively half as much twice as often, but note that the application depth is higher to account for evaporative losses at each event.
“Stress”	**S**	~75% AWC used up	25mm	10-14 days	This regime should maintain a soil moisture deficit – i.e. not return the soil to field capacity when irrigated.
“Excess” (2010 only)	**X**	~12.5% AWC used up	10mm	2-3 days	In effect, this regime keeps the soil as wet as practically possible to achieve.
“No Irrigation” (2010 only)	**N**	-	-	-	Zero irrigation after wetting to field capacity at the start of the season.

*Assuming typical loamy sand or sandy loam soil, with rooting zone of 300mm
**Assuming onion crop with rapidly growing or full canopy under typical June/July/August conditions (subject to rainfall)

AWC = Available water content

Table 8 Irrigation regimes in 2010, '11 and '12. Shading indicates "typical" practice (T/T/S).

Year	Trt	Name	Code	"Early" season L May to Initiation (E July)		"Mid" season Initiation (E Jul) to egg stage (E Aug)		"Late" season Egg stage (E Aug) to Stop		Stop
				Trigger	Target App^n	Trigger	Target App^n	Trigger	Target App^n	
2010	A	"Typical" with end season stress	T/T/S	50% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	B	"Typical", no extra stress	T/T/T	50% AWC	Return to FC	50% AWC	Return to FC	50% AWC	Return to FC	50% FO
	C	"Typical", no extra stress, extended	T/T/T.x	50% AWC	Return to FC	50% AWC	Return to FC	50% AWC	Return to FC	100% FO + 50% dead
	D	"Less-more-often", no extra stress	L/L/L	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	50% FO
	E	"Less-more-often", no extra stress, extended	L/L/L.x	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	100% FO + 50% dead
	F	"Excess"	X/X/X.x	12.5% AWC	Return to FC	12.5% AWC	Return to FC	12.5% AWC	Return to FC	100% FO + 50% dead
	G	"Stress" all season	S/S/S	75% AWC	50% of AWC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
	H	No irrigation	N/N/N	-		-		-		-
2011	A	"Typical", end season stress	T/T/S	50% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	B	"Typical" with mid+end season stress	T/S/S	50% AWC	Return to FC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
	C	"Typical" with early+ end season stress	S/T/S	75% AWC	50% of AWC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	D	"Less-more-often", no stress	L/L/L	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	50% FO
	E	"Less-more-often", end season stress	L/L/S	25% AWC	Return to FC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	F	"Less-more-often", mid+end season stress	L/S/S	25% AWC	Return to FC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
	G	"Less-more-often", early+end season stress	S/L/S	75% AWC	50% of AWC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	H	"Stress" all season	S/S/S	75% AWC	50% of AWC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
2012	A	"Typical", end season stress	T/T/S	50% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	B	"Typical" with mid+end season stress	T/S/S	50% AWC	Return to FC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
	C	"Typical" with early+ end season stress	S/T/S	75% AWC	50% of AWC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	D	"Less-more-often", no stress	L/L/L	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	50% FO
	E	"Less-more-often", end season stress	L/L/S	25% AWC	Return to FC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	F	"Less-more-often", end season "stress" irrigation at 100% FO	L/L/S+	25% AWC	Return to FC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO but 10mm @ 2 days before harvest
	G	"Less-more-often", "typical" mid-season, end season stress	L/T/S	25% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
	H	"Stress" all season	S/S/S	75% AWC	50% of AWC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO

AWC = Available Water Content within rooting zone (assumed to be 30cm).
FC = Field Capacity within rooting zone (assumed to be 30cm).
FO = canopy fall-over

Plot layout at each site is presented in Figure 3 and Figure 4 while Figure 5 and Figure 6 illustrate the two sites.

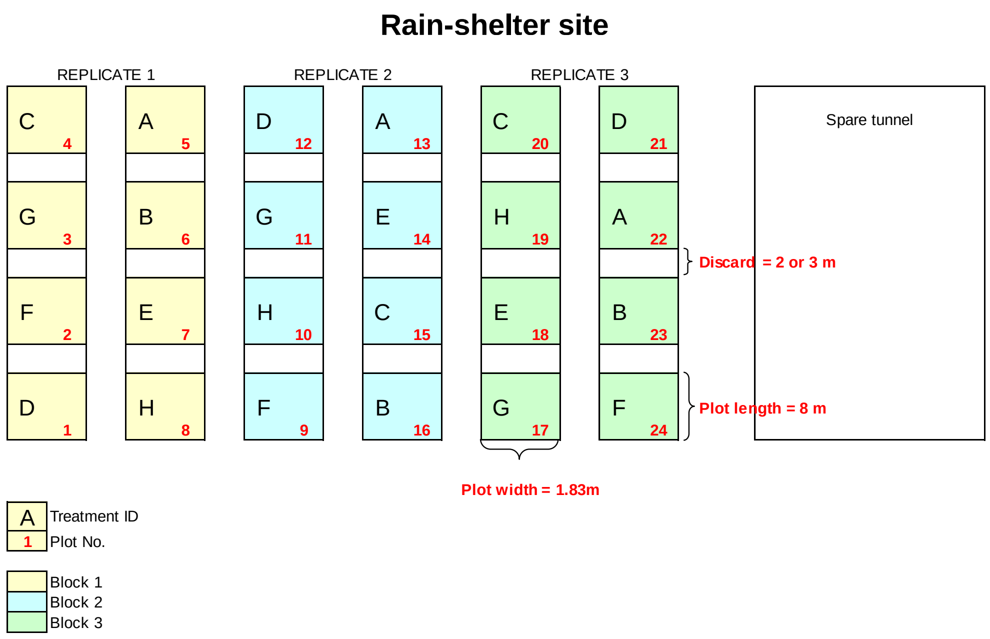


Figure 3 Plot layout at rain-shelter sites (note that 2011 and 2012 had a spare tunnel)

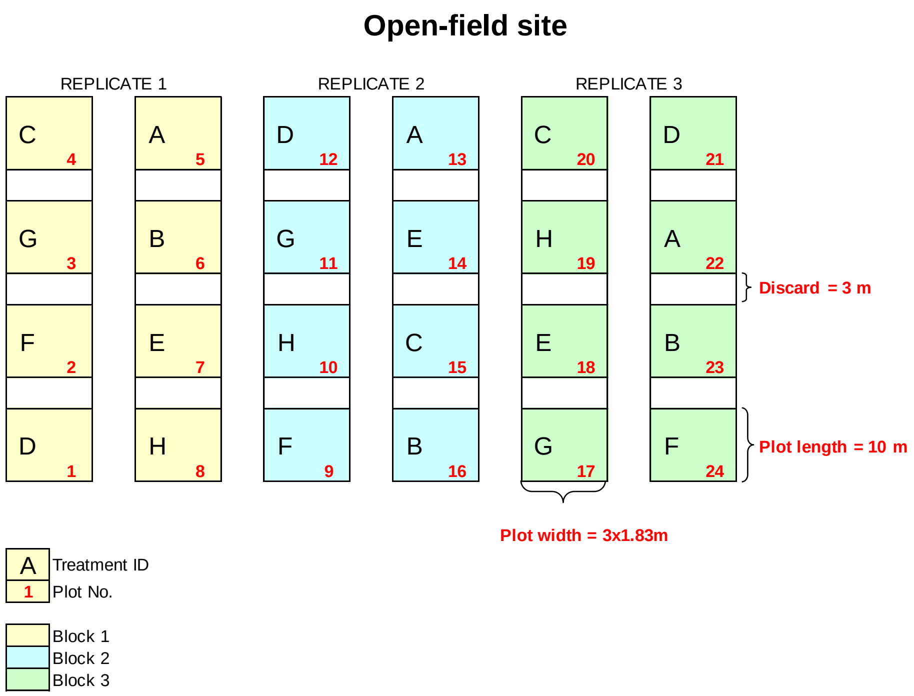


Figure 4 Plot layout at open-field sites.

Figure 5 Rain-shelter site (replicate 1) on 11th July 2012 (during irrigation event).

Figure 6 Open-field site (replicate 2) on 7th July 2012

Weather / soil moisture monitoring and irrigation scheduling

Irrigation events were scheduled using data from Decagon 10HS soil moisture sensors at 10, 20 and 30cm depths in each plot. All sensors were connected to an iMetos weather station, with data downloading to a secure web-site. All sites were saturated using plot sprinklers (if no recent rain) near the start of the season and allowed to drain for 48 hours to determine field capacity (FC) in order to calculate soil moisture deficit (SMD) for each treatment (as the mean of the 3 replicate plots).

To calculate trigger values for irrigation events, reference values for permanent wilting point (PWP) at the site in 2010 (Hall *et al*, 1977) and the measured FC were used to determine available water content (AWC). The appropriate SMD trigger irrigation for each treatment (as an average of the 3 replicate plot values) was then calculated using the percentage of AWC values in Table 8. To improve accuracy in 2011 and 2012, PWP figures calculated as average values from the non-irrigated plots in 2010 were used instead of reference values for the calculations.

Irrigation was applied using Dan mini-sprinklers, with layouts designed by the supplier to maximise uniformity of application within each trial plot. At each irrigation event, multiple rain gauges were placed in each plot to verify the amount of irrigation applied. Note that the depth of water applied at each irrigation event was calculated from Table 8 plus 2-3mm to account for evaporative losses from the soil surface immediately after irrigation.

Crop performance

The impact of irrigation regimes on crop performance was evaluated using a number of parameters as detailed below.

Crop establishment was measured using 3 randomly placed replicate counts of bulbs harvested from a 1 m section of bed (measured at harvest).

Crop canopy growth was measured approximately weekly (2010) or fortnightly (2011 and 2012) using a spectral ratio meter (Skye Spectrosense 2) to determine the percentage green cover at a reference point in each plot. Crop vigour was assessed visually at approximately fortnightly intervals (on a scale of 0 = dead to 10 = extremely vigorous). At approximately 4-week intervals, crop biomass was assessed by weighing a sub-sample of 10 randomly selected plants per plot (avoiding an area of 3m of bed in the centre of the plot for final yield harvests).

As the crop neared maturity, fall-over progression was noted (as a visual estimation of percentage fallen over and percentage senesced). At harvest, 3 replicate samples of 1 m x 1 bed were hand harvested (with tops removed) from the centre of the bed, counted for population data, netted and weighed to assess green bulb yield. All samples were then placed in a commercial refrigerated onion store for further assessments after curing and storage until approximately May the following year. Note that extended storage was used in an attempt to emphasise treatment differences.

Observations in 2011 indicated that there may have been some differences in the proportion of plants “bolting” (prematurely flowering) between treatments. Consequently, although it was not originally programmed for assessment, counts of the number of bolting plants per plot were made prior to harvest in 2011 and 2012. Counts were converted into percentage bolting using the average plant population counts from each plot.

All samples in long-term storage were assessed for dried bulb yield and bulb size (<45mm, 45-60mm, >60-80mm, >80-90mm and >90mm, graded on square grids). A variable "typical bulb diameter" was created as a single measure to describe the size of bulbs within a sample. This was calculated as an average bulb diameter by assuming all bulbs within a size grade lay at the centre of that range (e.g. 45-60mm was assumed to be an average of 52.5mm diameter, >60-80mm was assumed to be 70mm and 80-90mm was assumed to be 85mm) and that bulbs in the <45mm category were typically 40mm and those in the >90mm category were 95mm diameter. Although this method did not account for skewed data within categories, it provided a useful single measure for comparison of the sample size spectrum.

Post-storage bulb quality was also assessed to include: internal and external diseases; internal disorders (externally visible doubles and internal dead growing tips); visual assessment of skin quality on a scale of 0 = no skin to 5 = very thick skins and; internal regrowth on a scale of 0 = no regrowth to 5 = green shoot extending out of top of bulb. In addition, a sub-sample of 3 bulbs per sample were analysed for dry matter content by cutting in half longitudinally and drying at 80°C for 3 days.

Note that, in considering yields (either green or post-storage) throughout this document, field experience suggests that hand-harvested samples tend to yield around 15-20% higher than commercial mechanical harvesting – largely due to losses of under-size and also some in-spec bulbs during the process.

Crop pest and disease

Crop pest and disease incidence and severity was visually assessed every 2-3 weeks for: downy mildew (*Peronospora destructor*); leaf blight (*Botrytis squamosa*); leaf blotch (*Cladosporium allii* / *C. allii-cepae*); secondary bacterial infection on foliage, and; bacterial rots in bulbs. The severity of onion thrip (*Thrips tabaci*) damage was visually assessed at harvest only. Observations were made on a scale of 0 = no infection/infestation to 10 = extreme infection/infestation.

Soil nitrogen leaching

The impact of irrigation regimes on nitrate leaching from the soil was evaluated by assessment of soil mineral nitrogen (as ammonium, NH_4 and nitrate, NO_3) at the start (immediately prior to commencing irrigation), middle and end of the season (harvest). Multiple samples were taken from each plot at 0-30cm and 30-60cm and amalgamated to a single composite sample for each depth. Samples were kept cool and sent for analysis at Anglian Soil Analysis Ltd. as soon as practical after sampling.

In the previous annual reports, very large variability in absolute soil NH_4 and NO_3 concentrations at 0-30cm and 30-60cm soil profiles were observed and there were few consistent trends identifiable. Therefore, relative changes in the 30-60cm profile from either the start to middle of the season or start to end of season were calculated to try to provide a better indication of the impact of irrigation regimes on soil nitrogen leaching.

Weed response

Weed response to irrigation regimes was monitored by visual assessment of total weed levels prior to harvest (on a scale of 0 = no weeds to 10 = extreme weed pressure).

Irrigation efficiency, cost-benefit and identifying optimal irrigation regimes

Crop yield and quality data after storage was used to calculate the irrigation efficiency of the tested regimes as Water Use Efficiency, WUE (Hunt and Kirkegaard, 2012). WUE is assumed in this report to describe yield (as tonnes per hectare, post-storage) per millimetre of water received by the crop in the period from 2 months after planting (approximately mid-May, 2-3 true leaves) until harvest. This starting point was chosen to represent the period during which rapid crop growth commences and assumes sufficient soil moisture present up to this time to enable non limited crop growth.

Two measures of water received by the crop were used:

A. Sum of all rainfall and irrigation events during the defined time-period.
B. An adjusted measure using the data as above, but with the following assumptions:
    - An average of 1mm of each daily rainfall/irrigation total evaporated from the soil surface before infiltration.
    - Therefore, all rainfall/irrigation <1mm per day would not infiltrate into the soil.
    - Any rainfall/irrigation events >25mm would generate run-off beyond 25mm which would not infiltrate into the soil.
    - Any rainfall/irrigation events occurring when the total rainfall/irrigation in the previous day exceeded 25mm would also be counted as run-off.

This second measure of water received by the crop was introduced in order to try to refine the WUE relationship by accounting for water that was recorded, but would most likely not have infiltrated into the soil and be utilised by the crop. It is acknowledged that the assumptions used in this adjusted measure of water received are somewhat crude.

However, it was felt that this may provide a better estimate of the water actually received and therefore available for use by a crop.

A cost-benefit analysis was carried out for each irrigation regime in each year. This analysis assumed a typical growing cost of £3,250 per hectare (excluding irrigation) and curing, refrigerated storage and grading costs of £70/tonne (VCS, 2013a). Irrigation costs were assumed as presented in Table 9. Prices for post-storage marketable brown bulbs (excluding under-size, over-size and diseased bulbs) at farm-gate were assumed as presented in Table 10. Note that prices will vary according to both season and market demands.

Table 9 Irrigation costs assumed for cost-benefit analysis based on grower estimates and published figures (Morris and Adoho, 2013)

Element	Cost	Comment
Typical 25mm irrigation	£120 */ ha per irrigation*	Typically £85-£150, based on grower estimates and published figures
Of which "event" cost	£22.50 */ ha per irrigation*	Labour and tractor costs to move equipment
Of which water charge/pump	£32.50 */ ha per irrigation*	Volume-based EA abstraction charge and pumping costs, equivalent to £1.30 /mm/ha
Therefore typical "fixed" costs	£65.00 */ ha per irrigation*	Capital costs (infrastructure, equipment, maintenance etc)
Annual "fixed" costs	£390 */ha per annum*	Assuming 150mm per annum applied (i.e. 6x 25mm applications)
Calculated costs for:		
"Typical" 25mm irrigation	**£55 */ha per irrigation event***	**Plus annual fixed costs of £390 /ha**
"Less-more-often" 15mm irrigation	**£42 */ha per irrigation event***	**Plus annual fixed costs of £390 /ha**
"Excess" 10mm irrigation	**£35.50 */ha per irrigation event***	**Plus annual fixed costs of £390 /ha**

Table 10 Assumed farm-gate brown onion prices by size grade (AMI, 2013)

Size grade	Price	Comment
<45mm	£25 / tonne	40-60mm price = £100/tonne. It is assumed that a small proportion of <45mm onions would fit in the 40-45mm size range and so achieve this estimated value per tonne.
45-60mm	£100 / tonne	
60-80mm	£250 / tonne	Range £240-260
80-90mm	£200 / tonne	Processing market – typically volatile prices
>90mm	£50 / tonne	Little market for over-size

Total irrigation costs were calculated as the annual fixed costs (£390) plus the sum of the total number of irrigation events of each respective depth within each crop growth period (assuming 25mm for "typical" (T) or "stress" (S), 15mm for "L-M-O" (L) and 10mm for "excess" (X) events) multiplied by the event cost in Table 9.

Total production costs (£/ha) for each irrigation regime at each site and in each year were calculated by adding this irrigation cost to the typical growing cost and the curing, storage and grading costs for the quantity of onions that each regime had yielded.

Total gross returns (£/ha) for each irrigation regime at each site and in each year were calculated as the tonnage of marketable bulbs in each size grade yielded by each treatment multiplied by the assumed price per tonne in Table 10.

These analyses were used to help identify an optimal irrigation regime for bulb onions, ultimately helping to justify water use and demonstrate efficient irrigation to the Environment Agency for irrigation licence renewal in the future.

Statistical analysis

Data were subject to statistical analysis by the biometric department at Rothamsted Research. Analysis of variance (ANOVA) was used to determine differences between treatments and data were transformed where necessary. Where required, repeat measures ANOVA were used. All results are reported at a significance level of $p=0.05$.

Results

Weather, soil moisture monitoring / irrigation scheduling and crop growth

A summary of mean daily weather conditions during the growing season at the rain-shelter site and open-field site are presented in Figure 7 and Figure 8. For detailed summaries of individual year/site data, please refer to the respective annual report(s).

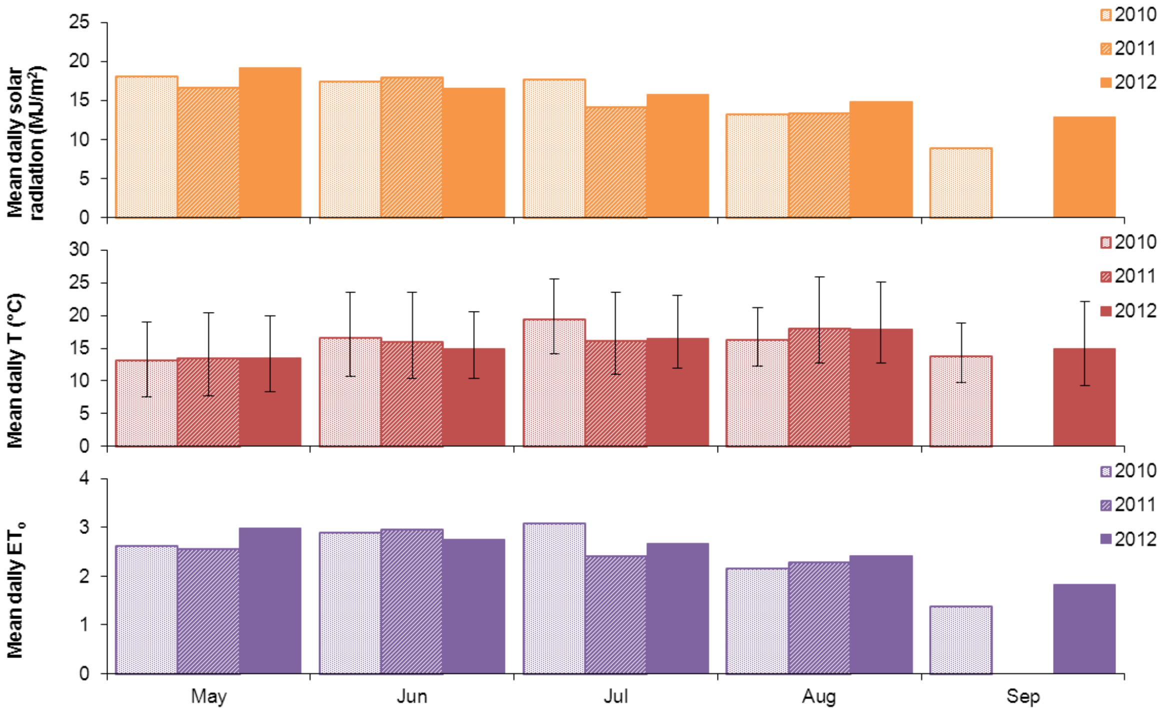


Figure 7 Weather under rain-shelters during growing season. Bars indicate mean daily maximum and minimum temperatures. Note that in 2011, the site was harvested in August.

The 2010 season was generally bright, warm and dry from May through to July, but with a very wet and cool end to the season. 2011 started with slightly brighter, warmer and drier conditions in May and early June, but then was wetter and cooler until August when conditions improved at the end of the season. In contrast, 2012 started cool and was wet from May through to August, but with a little improvement in time for a late harvest in September.

In all trial years, mean daily solar radiation was lower within the rain-shelter compared to outside (by between 7% and 14%, mean 11%). Daily minimum temperatures in the rain-shelter were very similar to outside, but maximum temperatures were considerably higher (by up to 13%), resulting in mean daily temperatures similar to or up to 3% higher than outside. As a result of the interaction between solar radiation, temperature, humidity and wind speed on reference evapotranspiration (ET_0), the overall effect of the rain-shelter was typically a reduction of around 5-8% in ET_0 compared to outside. Although this may have influenced crop growth under the rainshelters, this was considered to be acceptable, particularly when balanced against the benefits of reducing the risk of open-field trial failure due to wet conditions.

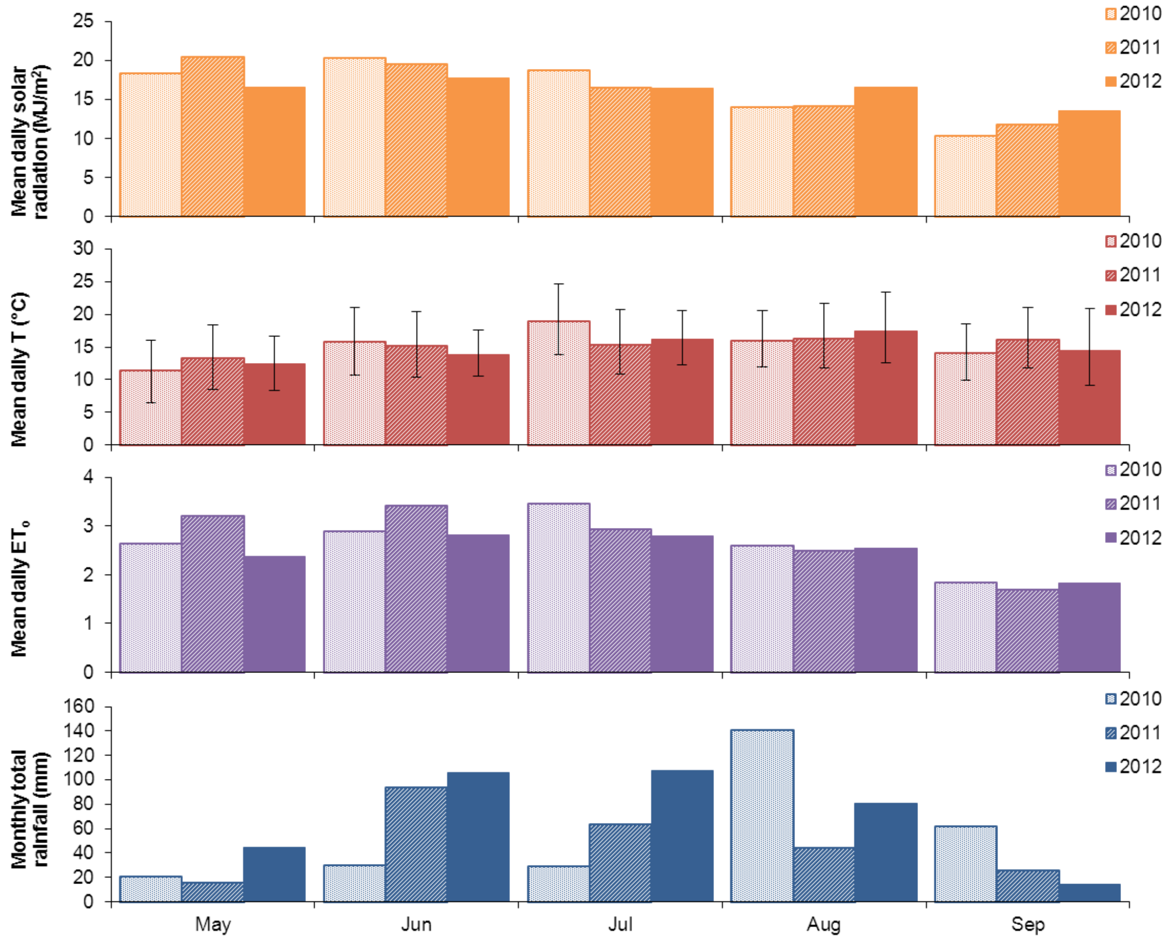
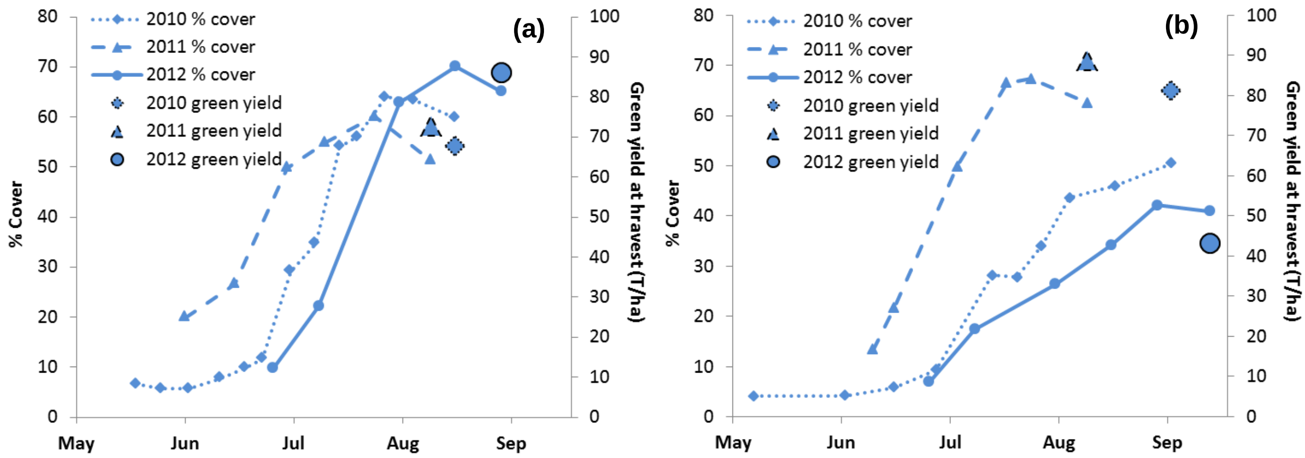


Figure 8 Weather at open-field site during growing season. Bars indicate mean daily maximum and minimum temperatures.

Figure 9 illustrates the impact of the differing seasons on crop development as % canopy cover and green yield at both sites under "typical" irrigation practice (T/T/S – treatment A).

Crop growth at the open-field sites was considerably more variable than under the rain-shelter, although similar patterns at both sites were noted. Crop growth in 2011 was much more forward early in the season due to the bright, warm and dry conditions in late spring, whereas the much cooler and wetter start to 2012 resulted in very slow crop development that could not recover to normal values at the open-field site. 2010 lay between these two extremes, with a relatively slow start, but good weather during the middle of the season



generally allowing the crops to catch up.

Figure 9 Comparison of crop performance under “typical” irrigation regime (treatment A, T/T/S) at rain-shelter site (a) and open-field site (b).

An example of 2012 soil moisture deficit (SMD) monitoring in the root zone and irrigation applications through the season for each treatment at the rain-shelter site is presented in Figure 10. For detailed summaries of individual year/site data, please refer to the respective annual report(s).

Table 11 summarises the number and depth of irrigations applied to each treatment after initial wetting to field capacity.

In general, irrigation regimes based on the “typical” field irrigation (using code “T”) were similar to typical field applications made by growers. Under such regimes, generally around 25mm would be applied every 7-10 days during the main crop canopy building phase and the start of bulbing. During a typical season, growers would expect to apply between 100 mm and 175mm in 4-7 x 25mm applications.

Regimes based on a “less-more-often” (“L-M-O”) principle (using code “L”) generally had around 13-15mm applied every 3-4 days and resulted in greater total application than the “typical” type treatments. “Excess” irrigation (2010 only – using code “X”) typically applied 9-10mm every 2-3 days and resulted in greater still application quantities. “Stress” periods (using code “S”) generally had around 25-30mm applied every 10-14 days.

It should be noted that the wet seasons of 2011 and 2012 significantly reduced irrigation requirements at the open-field trial site. Consequently, few irrigation applications were made, and there were very few significant difference observed between treatments. As a result, 2011 and 2012 open-field site data has been excluded from analysis and all data presented in this report are limited to 2010 (open-field and rain-shelter site), 2011 (rain-shelter site only) and 2012 (rain-shelter site only).

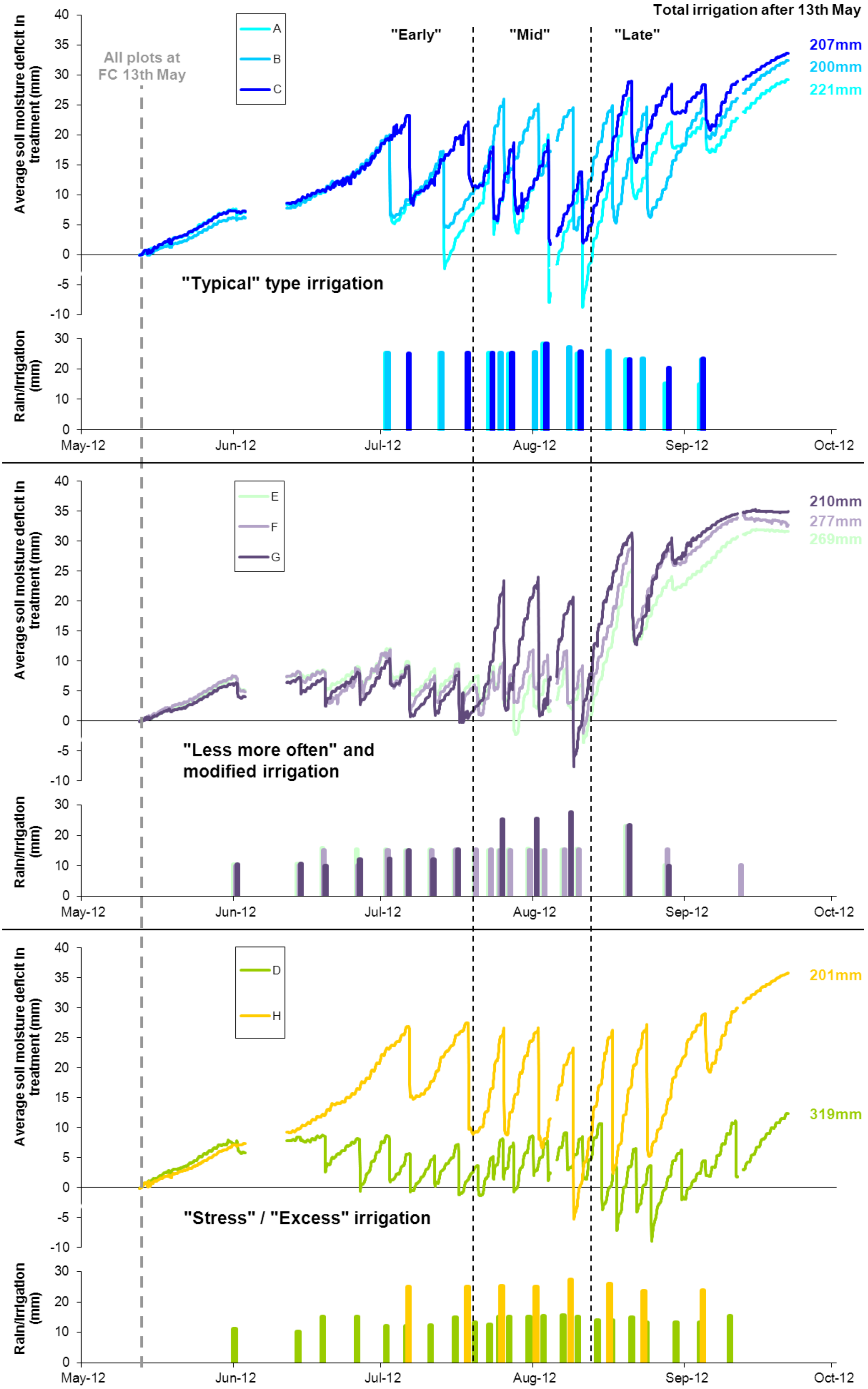


Figure 10 SMD in root zone and irrigation applications at the rain-shelter site 2012

Table 11 Summary of irrigation events applied to each treatment

Year	Trt	Name	Code	Rain-shelter Total number	Rain-shelter Total depth	Rain-shelter Mean depth	Open-field Total number	Open-field Total depth	Open-field Mean depth
2010	A	"Typical" with end season stress	T/T/S	7	163mm	23.3mm	5	124mm	24.8mm
	B	"Typical", no extra stress	T/T/T	7	155mm	22.1mm	6	154mm	25.7mm
	C	"Typical", no extra stress, extended	T/T/T.x	9	201mm	22.4mm	7	177mm	25.2mm
	D	"Less-more-often", no extra stress	L/L/L	16	230mm	14.4mm	11	166mm	15.1mm
	E	"Less-more-often", no extra stress, extended	L/L/L.x	19	261mm	13.8mm	14	207mm	14.8mm
	F	"Excess"	X/X/X.x	33	300mm	9.1mm	21	229mm	10.9mm
	G	"Stress" all season	S/S/S	4	120mm	30.0mm	3	88mm	29.3mm
	H	No irrigation	N/N/N	-	-	-	-	-	-
2011	A	"Typical", end season stress	T/T/S	8	193mm	24.1mm	2	55mm	27.5mm
	B	"Typical" with mid+end season stress	T/S/S	7	169mm	24.2mm	1	30mm	30.0mm
	C	"Typical" with early+end season stress	S/T/S	6	157mm	26.2mm	2	55mm	27.5mm
	D	"Less-more-often", no stress	L/L/L	21	280mm	13.3mm	5	83mm	16.6mm
	E	"Less-more-often", end season stress	L/L/S	17	216mm	12.7mm	4	64mm	16.0mm
	F	"Less-more-often", mid+end season stress	L/S/S	12	194mm	16.2mm	2	40mm	20.0mm
	G	"Less-more-often", early+end season stress	S/L/S	10	173mm	17.3mm	3	54mm	18.0mm
	H	"Stress" all season	S/S/S	5	128mm	25.5mm	1	30mm	30.0mm
2012	A	"Typical", end season stress	T/T/S	9	207mm	23.0mm	2	50mm	25.0mm
	B	"Typical" with mid+end season stress	T/S/S	8	200mm	25.1mm	1	23mm	23.0mm
	C	"Typical" with early+end season stress	S/T/S	9	221mm	24.6mm	2	50mm	25.0mm
	D	"Less-more-often", no stress	L/L/L	23	319mm	13.9mm	7	103mm	14.7mm
	E	"Less-more-often", end season stress	L/L/S	18	269mm	14.9mm	3	47mm	15.6mm
	F	"Less-more-often", end season "stress" irrigation at 100% FO	L/L/S+	19	277mm	14.6mm	4	57mm	14.2mm
	G	"Less-more-often", "typical" mid-season, end season stress	L/T/S	13	210mm	16.1mm	2	50mm	25.0mm
	H	"Stress" all season	S/S/S	8	201mm	25.1mm	1	23mm	23.0mm

Data analysis

For the purposes of this report, all data have been re-analysed over the three trial years (2010, 2011 and 2012) at the rain-shelter site, and 2010 only at the open-field site. Data from 2011 and 2012 at the open-field site were omitted due to the wet seasons which resulted in insufficient irrigation requirement at the site to generate meaningful data.

Data were analysed by blocks of comparable treatment regime / year in order to evaluate the following key comparisons:

- **The effect of whole season "extreme" irrigation regimes:**
  - *"Excess" irrigation (code X/X/X.x) compared to "typical" (T/T/S), "stress" (S/S/S) and "no irrigation" (N/N/N).*
  - *"Less-more-often" through season (L/L/L) compared to "typical" (T/T/S) and "stress" (S/S/S)*
- **The effect of irrigation timing and frequency:**
  - <u>Early</u> season until bulb initiation (early July):
    - *"Less-more-often" ("L-M-O") compared to "stress"*
    - *"Typical" compared to "stress"*
    - *"Less-more-often" compared to "typical" and "stress"*
  - <u>Mid-season</u> from bulb initiation (early July) to egg stage (early August):
    - *"Less-more-often" compared to "stress"*
    - *"Typical" compared to "stress"*
    - *"Less-more-often" compared to "typical" and "stress"*
  - <u>Late</u> season from egg stage (early August) until stop point:
    - *"Less-more-often" compared to "stress"*
    - *"Typical" compared to "stress"*
  - <u>Stop</u> point for irrigation:
    - *Stop at 50% fall-over compared to Stop at 100% fall-over + 50% dead*
    - *Stop at 50% fall-over compared to Stop at 50% fall-over but apply 10mm @ 2 days prior to harvest.*

Appendix 1 summarises the treatment regimes grouped over the 3 trial years, and indicates treatment/site/year blocks used for analysis.

Note that all data presented in this section identifies the relevant treatment blocks used for analysis beneath the X-axis, using the treatment codes as in Table 8, year and site reference (R = rainshelter, O = open-field). Note also that error bars in the first column indicate LSD for the rest of the comparable series and black outlines indicate statistically significant differences within comparable series ($p<0.05$).

The effect of whole season "extreme" irrigation regimes

<u>Crop establishment</u>

Established crop population at harvest is presented in Figure 11.

Whole season irrigation regimes did not significantly influence population at the time of harvest. Populations were generally close to or higher than the target 52 plants/m^2 at the rain-shelter site, but lower than the grower-led target of 48 plant/m^2 at the open-field site – largely reflecting the better conditions for establishment at the rain-shelter site.

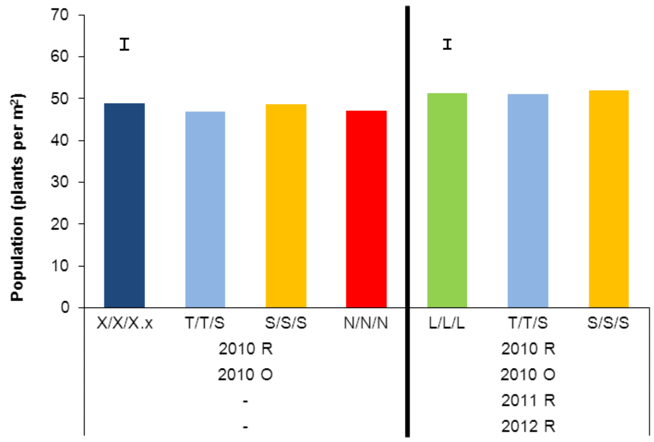


Figure 11 Established crop population at harvest. See page 25 for details of abbreviations.

<u>Crop growth</u>

Crop growth as percentage green cover measured in late June, mid July and early August and as fresh plant biomass in late June and late July is presented in Figure 12.

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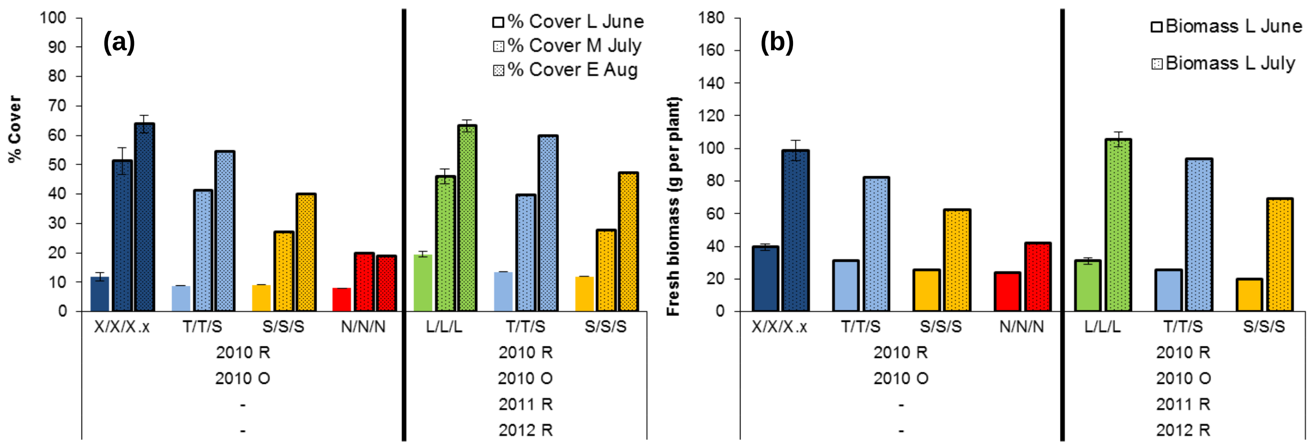

Figure 12 Crop canopy growth as % green cover (a) and fresh plant biomass (b).

There were no significant effects of irrigation regime on crop canopy cover at late June assessments, although crop biomass at this time was significantly greater in “wetter” regimes than “stress” or no irrigation. By early August, more frequent applications of water drove significantly greater canopy growth and biomass than “typical”, “stress” or no irrigation regimes.

Fall-over timing and bolting

Fall-over timing as days after drilling (DAD) when >50% of plants had fallen over and the proportion of bolting plants at harvest are presented in Figure 13.

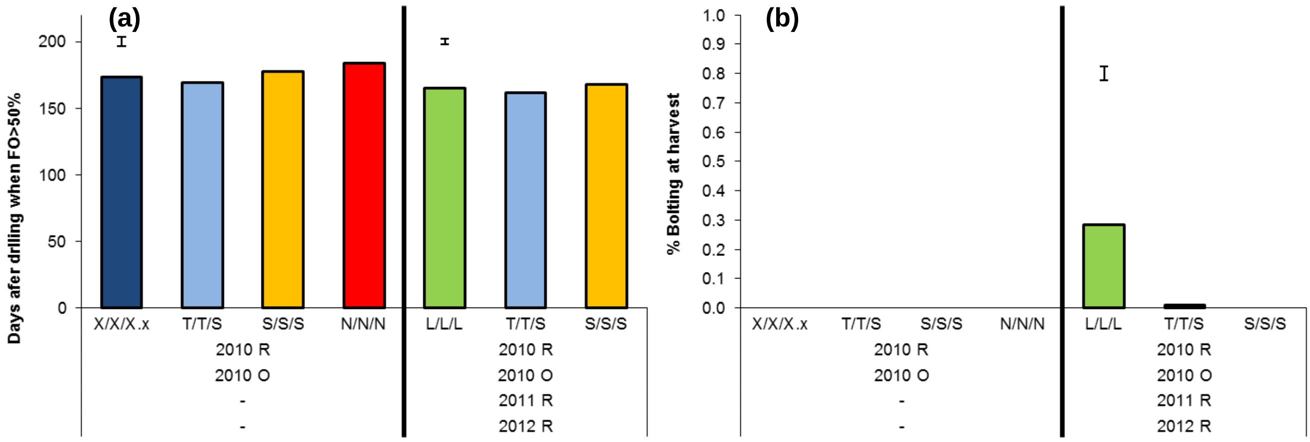

Figure 13 Days after drilling when fall-over >50% (a) and proportion of bolting plants at harvest (b).

There were significant differences in fall-over timing between irrigation regimes, with those providing “typical” or more frequent water falling over sooner than “stress” or non-irrigated treatments, but with no differences between “typical” and the wetter X/X/X.x or L/L/L regimes.

“Less-more-often” irrigation appeared to significantly increase bolting risk over “typical” or “stress” irrigation. However, it should be noted that bolting was very seasonally variable (none in 2010, more in 2011 and little in 2012) and the proportions affected were low.

Post-storage yield and bulb diameter

Post-storage yield and typical bulb diameter at harvest is presented in Figure 14.

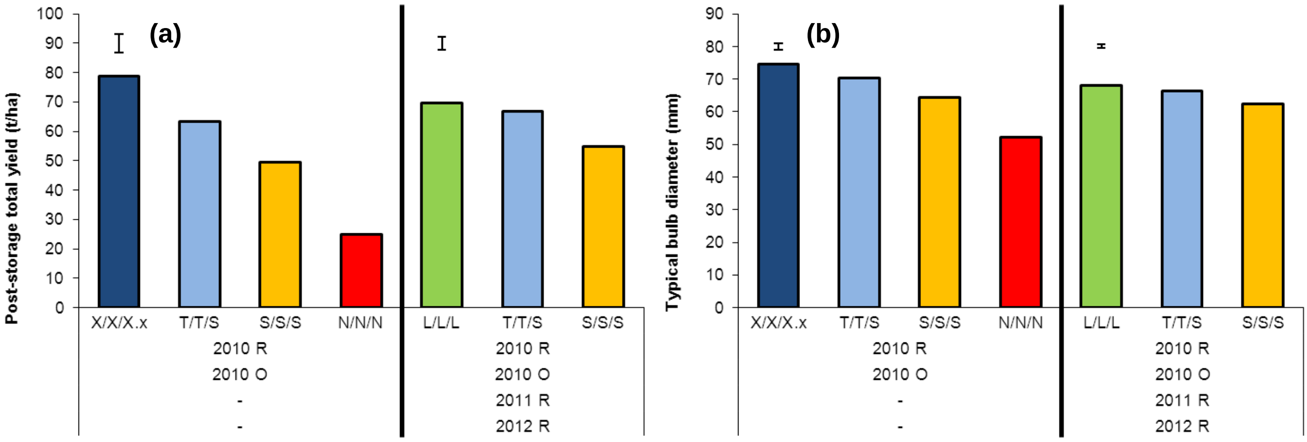

Figure 14 Post-storage yield (a) and typical bulb diameter (b).

Yield was generally significantly higher in irrigation regimes with progressively more frequent applications, although the yield under “less-more-often” was not significantly higher than under “typical” irrigation regimes.

Given that populations were unaffected by irrigation regime, it is unsurprising that most of the increase in yield came as a result of larger bulbs within the “wetter” regimes.

Post-storage diseases, internal disorders and skin quality

Post-storage diseases, internal disorders and skin quality data are presented in Figure 15.

There were only significant differences between irrigation regimes in the proportion of bulbs with bacterial rots after storage, with non-irrigated treatments having significantly more bacterial rots than “typical”, “stress” or “excess” regimes. However, this pattern was not reflected in the other irrigation regimes analysed in these blocks. There were no significant differences in the occurrence of either *Fusarium*, *Botrytis* neck rot or other bulb diseases.

There were also no significant differences in the occurrence of internal disorders, although there was a slight trend to indicate that wetter irrigation regimes may tend to cause more doubles than drier regimes. There were also no significant effects of irrigation regime on skin quality score.

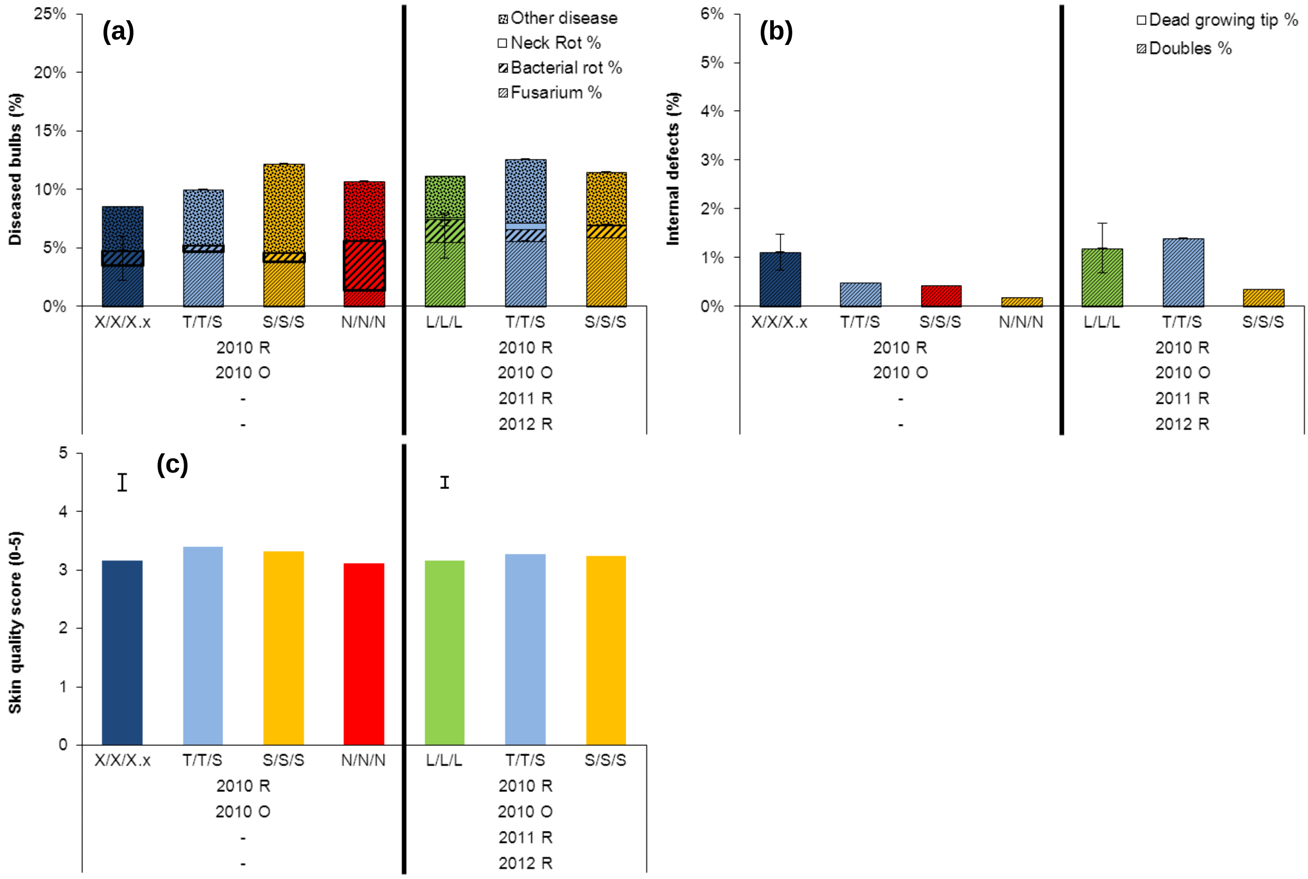

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Figure 15 Post-storage diseases (a), internal disorders (b) and skin quality score (c).

Post-storage bulb re-growth and dry matter content

Post-storage bulb re-growth scores and dry matter content are presented in Figure 16.

Bulb re-growth was significantly greater in treatments with “excess” irrigation and no irrigation than “typical” or “stress” irrigation, although this did not follow a clear pattern between regimes.

Bulb dry matter was significantly lower in “less-more-often” regimes than “typical” or “stress” irrigation, but was also not consistent across regimes.

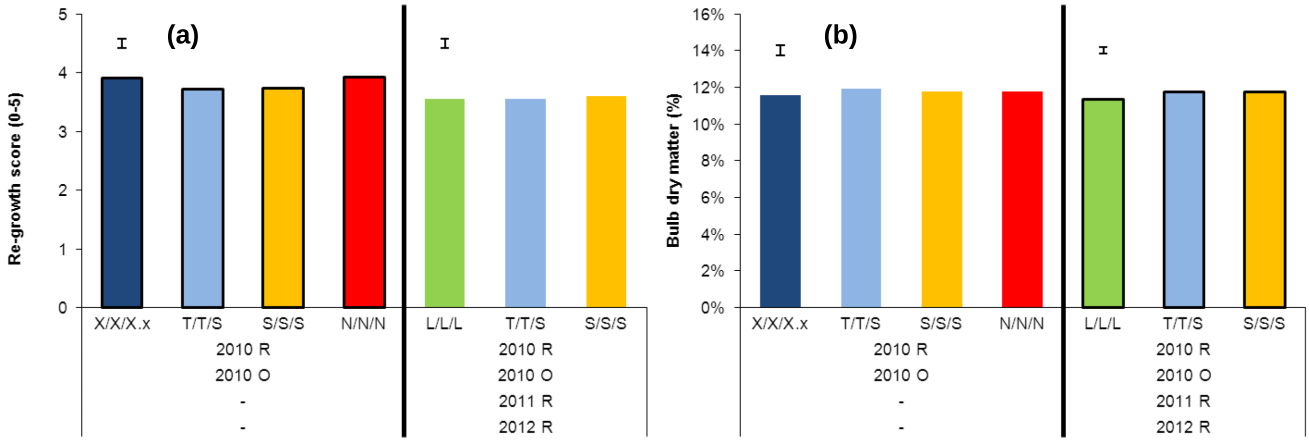

Figure 16 Bulb re-growth score (a) and dry matter content (b).

Foliar disease severity

The maximum observed downy mildew and *Botrytis* leaf blight scores during the season are presented in Figure 17.

Note that since there were no significant differences in observations of *Cladosporium* leaf blotch, secondary bacterial infections or bacterial rots, these data were not presented here. Downy mildew was significantly more severe in irrigation regimes that applied more frequent water than “typical” or “stress” regimes. There were also significant differences in *Botrytis* leaf blight severity between regimes that applied more frequent water compared to “stress” or no irrigation regimes but no difference between “excess” or “less-more-often” and “typical” regimes.

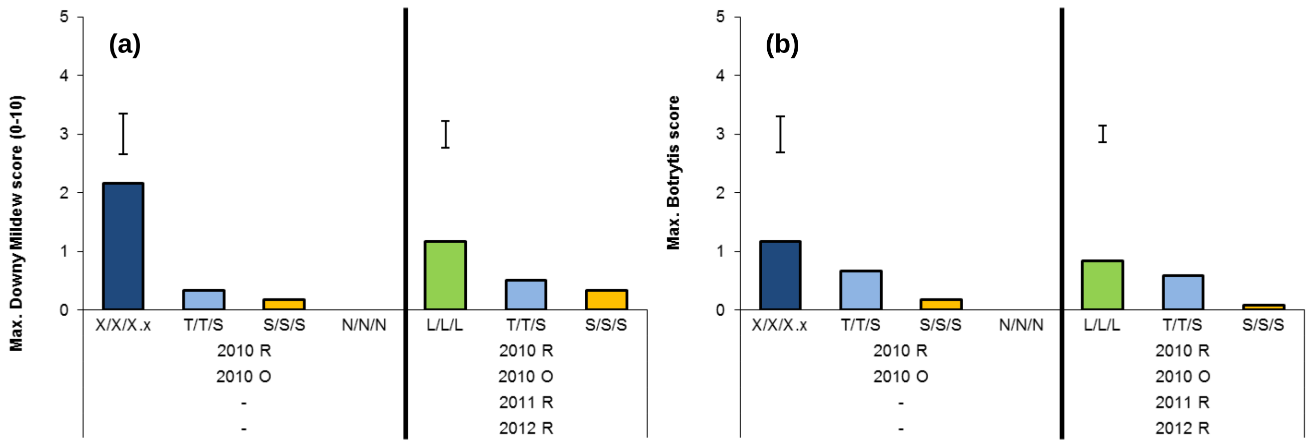

Figure 17 Maximum observed downy mildew score (a) and *Botrytis* leaf bight score (b).

Thrip damage severity and weed levels

Thrip damage severity scores and weed level scores at harvest are presented in Figure 18.

Thrip damage was significantly more severe with decreasing frequency of irrigation applications. Weed levels were generally higher under more frequent irrigation, but were somewhat inconsistent.

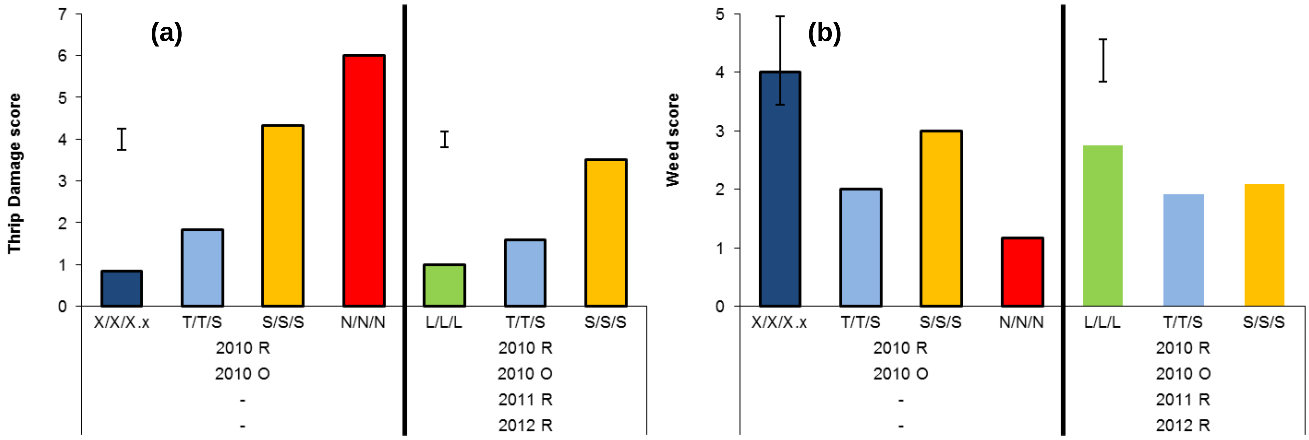

Figure 18 Thrip damage severity score (a) and weed level score (b).

Soil nitrogen leaching

Figure 19 and Figure 20 present the relative change in soil ammonium (NH_4) and nitrate (NO_3) concentration for the periods: start (before irrigation regimes commenced) to middle of season, and; start to end of season (harvest), respectively.

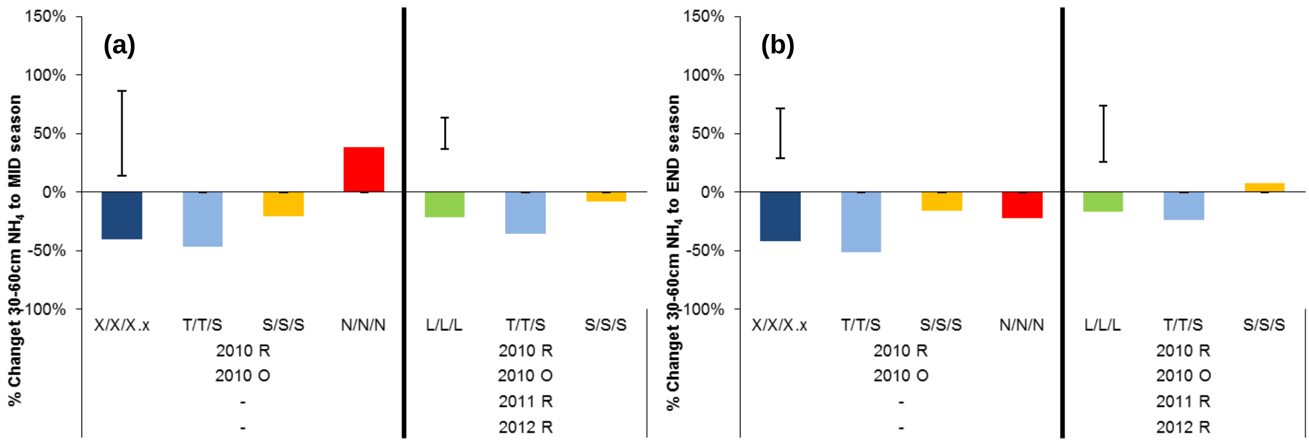

Figure 19 Relative change in NH_4 from start of season to mid-point (a) and harvest (b).

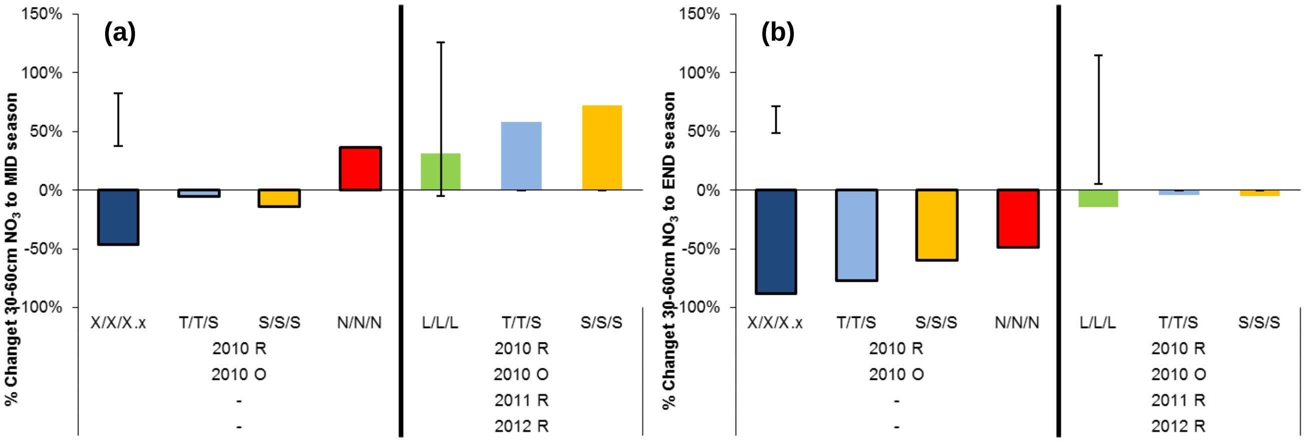

Figure 20 Relative change in NO_3 from start of season to mid-point (a) and harvest (b).

There were no significant differences in the relative change in NH_4 concentration at 30-60cm either to the middle or the end of the season, although there were some slight indications that the "wetter" regimes may have tended to decrease levels more than the drier ("stress" / no irrigation) regimes.

The relative change in NO_3 concentration at 30-60cm showed a similar but statistically significant pattern, with the "excess" irrigation (X/X/X.x) showing significantly greater reduction in NO_3 than no irrigation (N/N/N) by mid-season, and also compared to "stress" irrigation (S/S/S) by the end of the season. There were no significant differences between "excess" and "typical" irrigation, between "typical" and "stress" irrigation, or between "stress" and no irrigation. Looking at the less extreme irrigation regimes (less-more often compared to "typical" compared to stress), there were no significant differences in the relative change of NO_3 – although a similar pattern was observed.

The effect of irrigation timing and frequency/volume

Note that to limit the presentation of unnecessary data, only those with significant or relevant results are presented in this section.

As with the previous section: all data presented here identifies the relevant treatment blocks used for analysis beneath the X-axis; error bars show LSD for comparable series, and; black outlines indicate statistically significant differences within comparable series (p<0.05).

<u>Crop establishment</u>

Established crop population was not significantly affected by timing and frequency/volume of irrigation applied during the season, therefore data is not presented here.

<u>Crop growth</u>

Crop growth as percentage green cover and as fresh plant biomass is presented in Figure 21 and Figure 22 respectively. Note that only data relating to the effect of irrigation during the early and middle part of the season are presented, since late-season irrigation and stop timing could have no effect on crop cover or biomass measured earlier in the season.

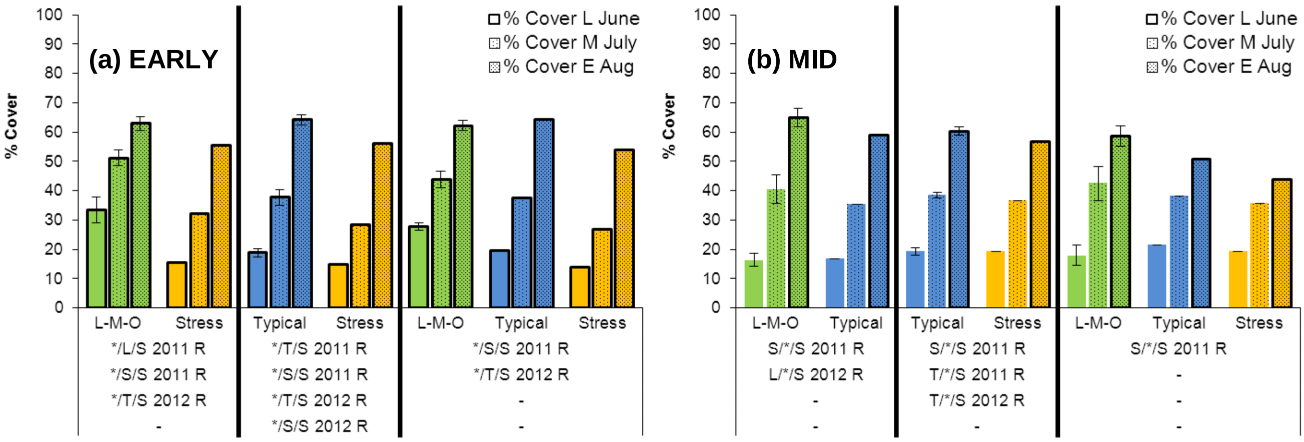

Figure 21 Crop canopy growth as % green cover as a result of irrigation treatment during early season (a) and mid-season (b).

"Less-more-often" ("L-M-O") irrigation during the early season period (typically late May to early July) generated significantly greater canopy cover than "typical" irrigation by late June and mid-July. However, by early August, canopy cover in treatments with "typical" irrigation early in the season had recovered to similar levels to "L-M-O" treatments. "Stress" regimes during the early period significantly reduced canopy cover development all through the remaining season.

"L-M-O" during the mid-season period (typically early July to Early August) generated significantly greater canopy cover than "typical" irrigation by early August. Again, "stress" during the mid-season significantly reduced canopy from "L-M-O" or "typical" irrigation regimes.

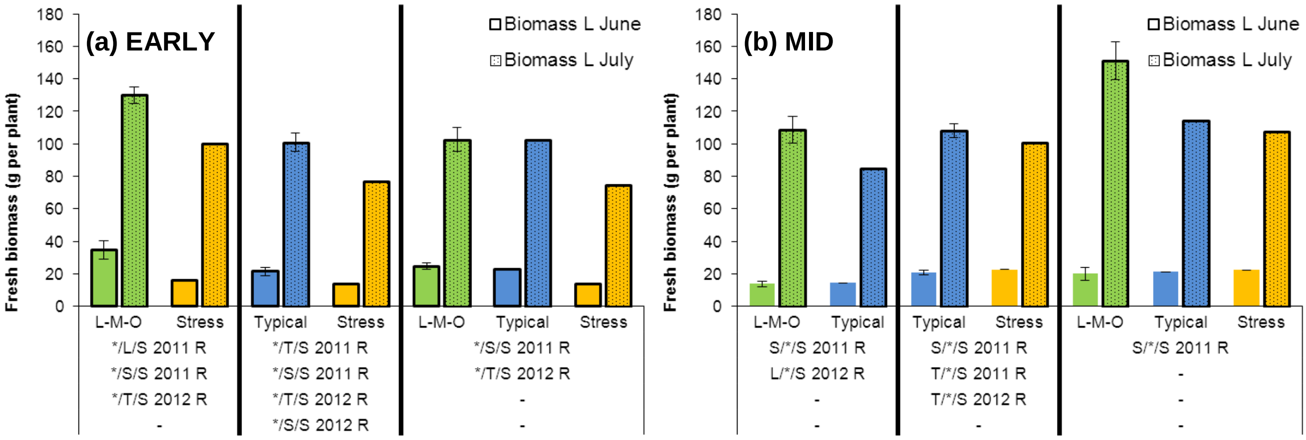

Figure 22 Fresh plant biomass as a result of irrigation treatment during early season (a) and mid-season (b)

Similarly to crop cover data, "stress" regimes during the early season also significantly reduced crop biomass when compared to "L-M-O" or "typical" irrigation. However, despite increases in crop canopy cover, there were no significant increases in crop biomass as a result of early season "L-M-O" compared to "typical" irrigation.

Plant biomass by early August was significantly greater in treatments with "L-M-O" during the mid-season than "typical" irrigation. "Typical" irrigation also resulted in significantly increased biomass when compared to "stress".

Fall-over timing

Fall-over timing as days after drilling (DAD) when >50% of plants had fallen over is presented in Figure 23.

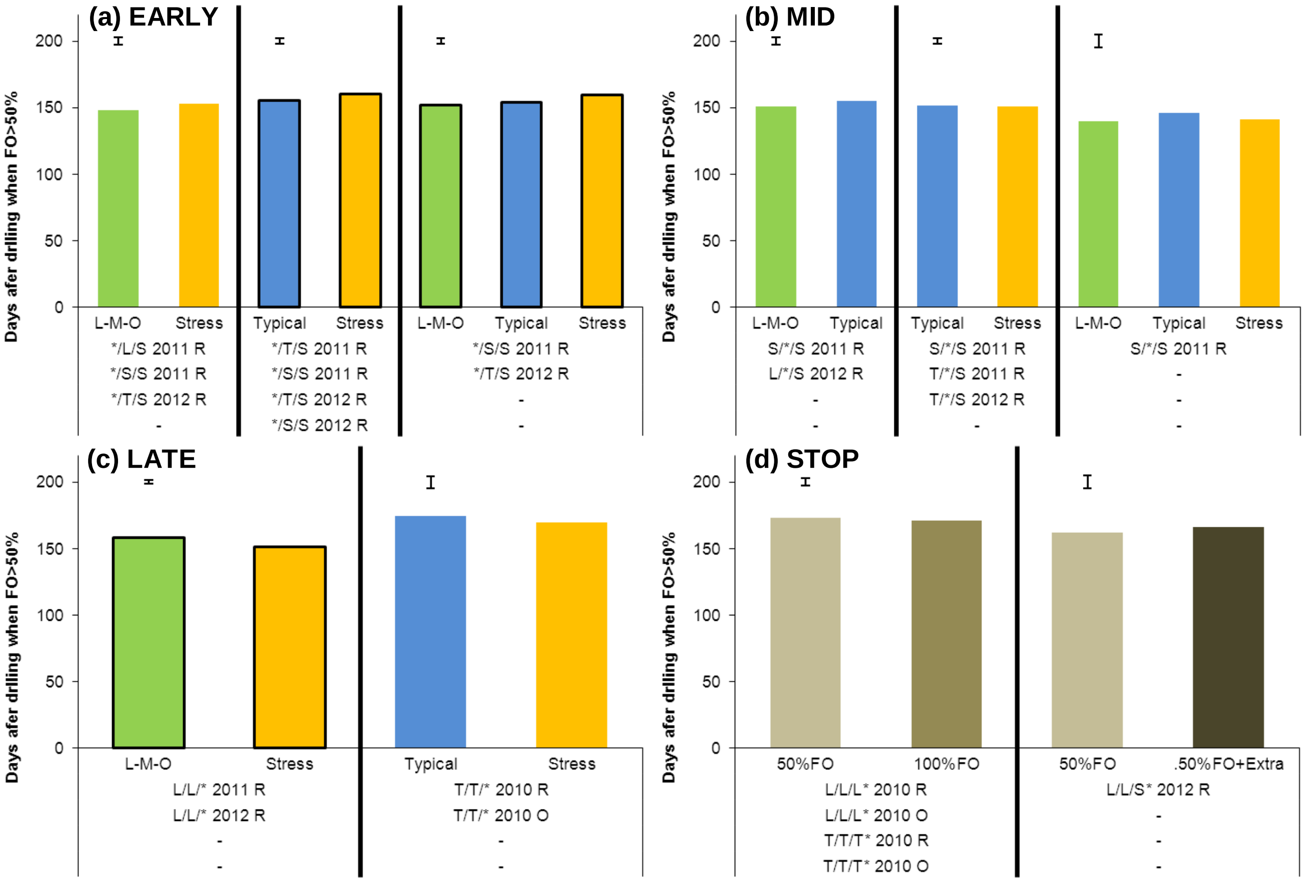

Figure 23 Days after drilling when crop fall-over >50% as a result of irrigation treatment during early season (a), mid-season (b), late season (c) and stop timing (d).

There were indications that more intense early season irrigation caused fall-over to progress more rapidly (statistically significant in two out of three analysis blocks). There were also indications that late season “L-M-O” significantly slowed fall-over progression compared to “stress” irrigation.

Bolting at harvest

The proportion of bolting plants at harvest are presented in Figure 24

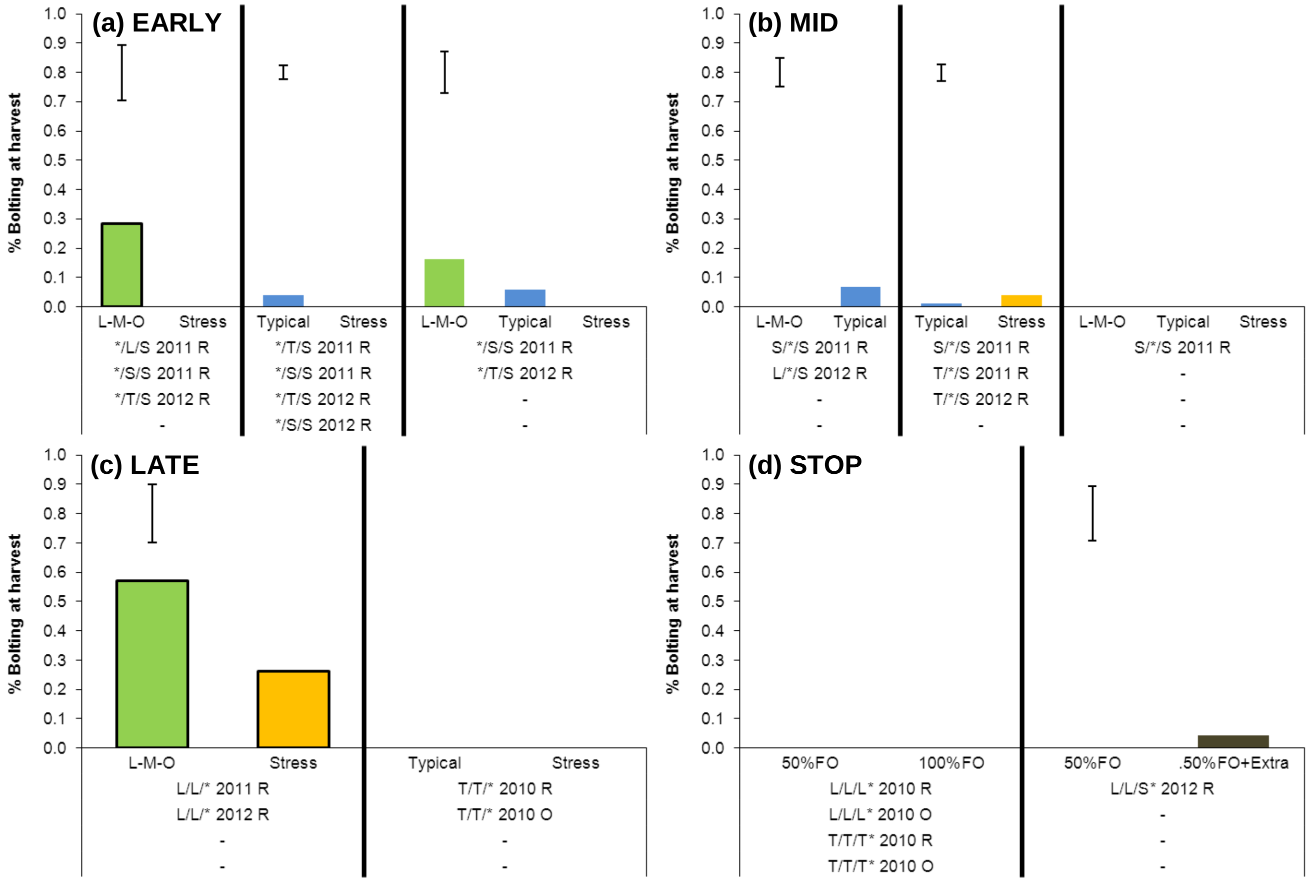

Figure 24 Proportion of bolting plants at harvest as a result of irrigation treatment during early season (a), mid-season (b), late season (c) and stop timing (d).

The proportion of bolting plants was significantly higher where “L-M-O” treatments were applied early in the season or late in the season when compared to “stress” irrigation. However, there were no significant differences when compared to “typical” irrigation or as a result of irrigation regime during mid-season or stop timing.

Post-storage yield

Post-storage yield is presented in Figure 25.

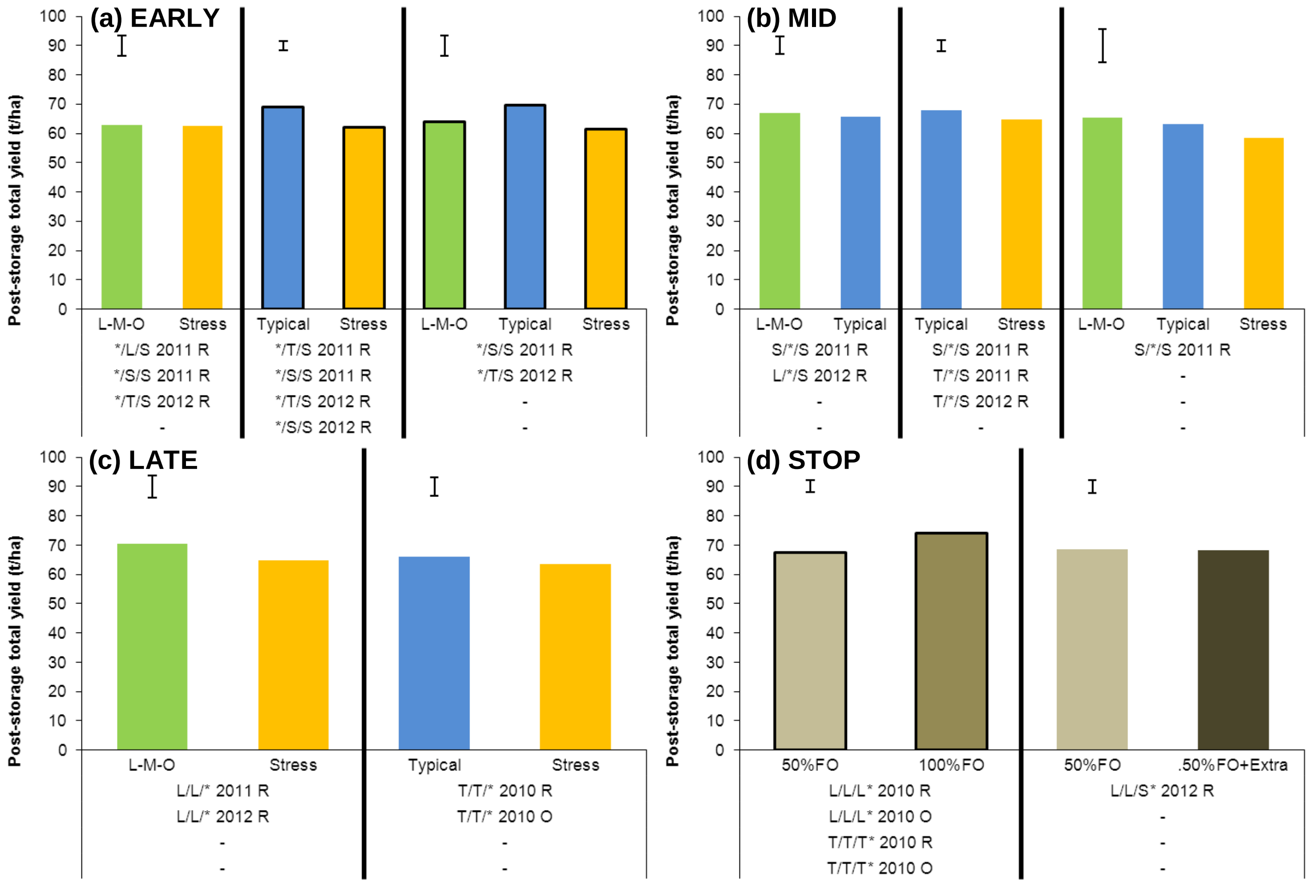

Figure 25 Post-storage yield as a result of irrigation regime during early season (a), mid-season (b), late season (c) and stop timing (d).

“Typical” irrigation during early season significantly increased post-storage yield over “stress” regimes, but there was no further increase from “L-M-O” irrigation at this period. There were no significant differences in yield as a result of the irrigation regime during mid or late season, although there was a trend to suggest that more frequent irrigation increased yield. Irrigating to 100% fall-over instead of 50% fall-over significantly increased yield.

Post-storage bulb diameter

Post-storage typical bulb diameter is presented in Figure 26.

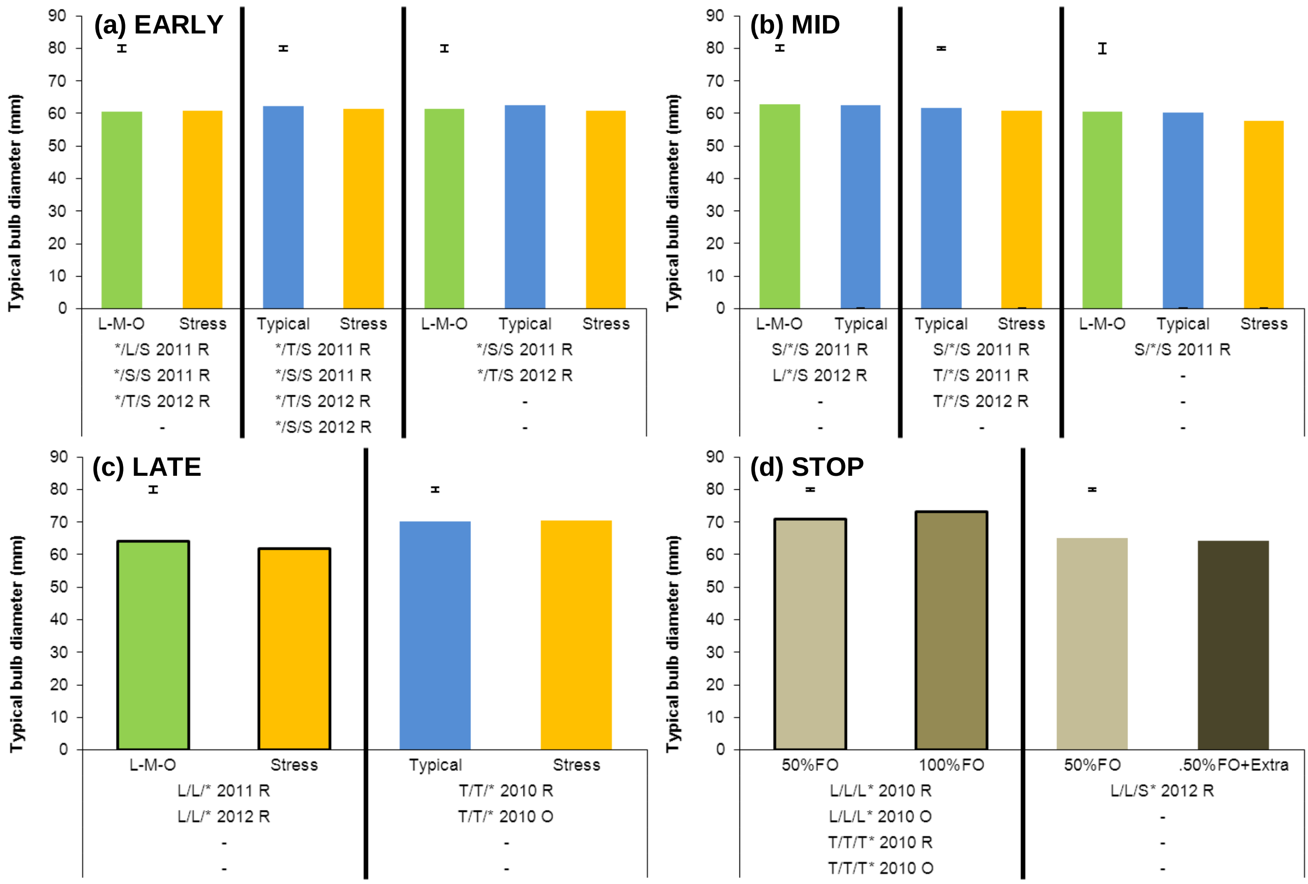

Figure 26 Post-storage typical bulb diameter as a result of irrigation regime during early season (a), mid-season (b), late season (c) and stop timing (d).

There was little effect of irrigation regime during early or mid-season on post-storage typical bulb diameter. However, late-season irrigation appeared to significantly increase bulb size ("L-M-O" compared to stress, but no significant difference between "typical" and stress). Irrigating to 100% fall over compared to 50% fall over also significantly increased bulb size.

Post-storage diseases

Post-storage diseases are presented in Figure 27.

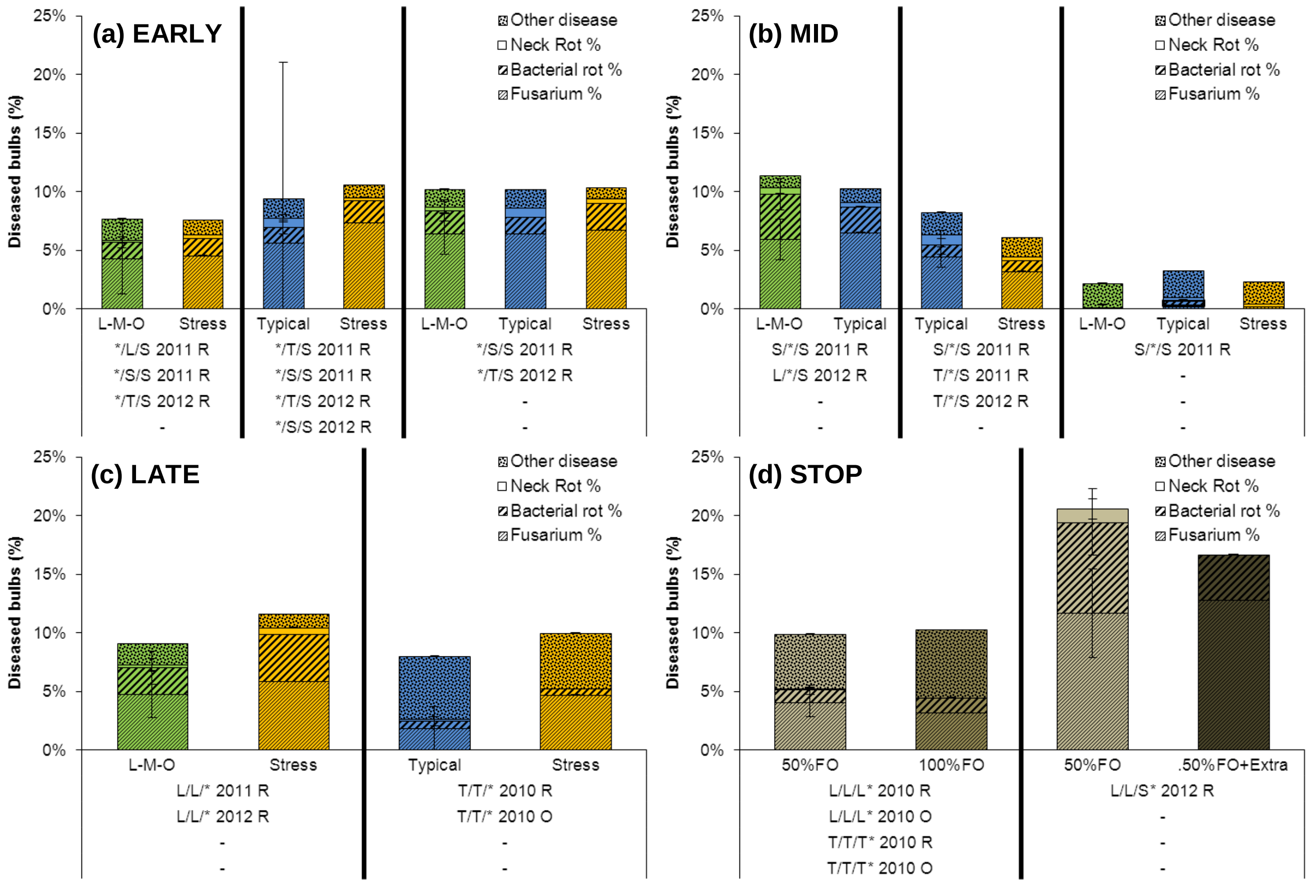

Figure 27 Post-storage diseases as a result of irrigation regime during early season (a), mid-season (b), late season (c) and stop timing (d).

Although there was one statistically significant result noted, there were no consistent trends to suggest that post-storage bulb diseases varied as a result of the irrigation regime applied during the season or the time of irrigation stopping.

Post-storage internal disorders and skin quality

Post-storage internal disorders are presented in Figure 28. There were no significant differences in skin quality score as a result of irrigation regime during the season, therefore this data is not presented here.

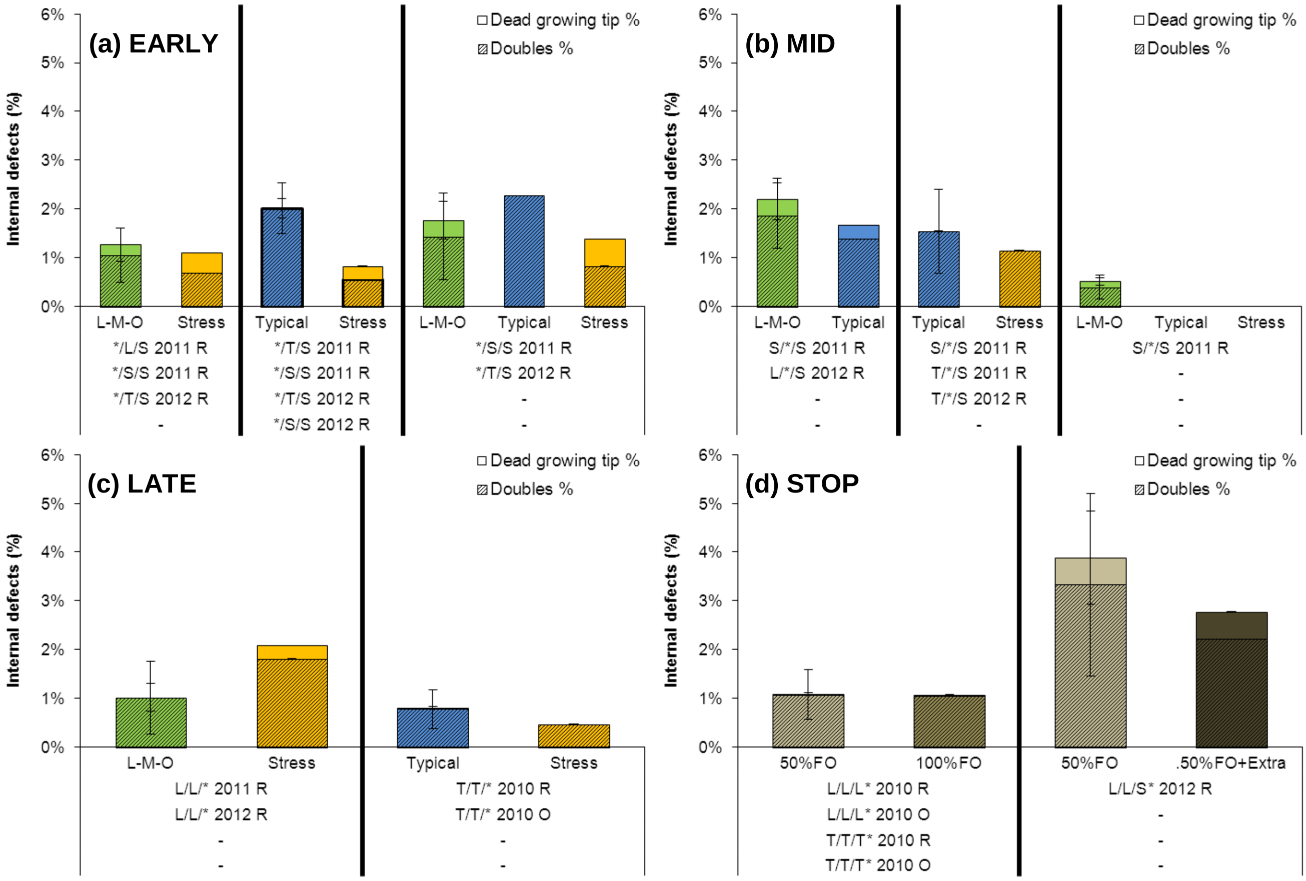

Figure 28 Post-storage internal defects as a result of irrigation regime during early season (a), mid-season (b), late season (c) and stop timing (d).

Although there was one statistically significant result noted, there were no consistent trends to suggest that post-storage internal defects varied as a result of the irrigation regime applied during the season or the time of irrigation stopping.

Post-storage bulb re-growth

Post-storage bulb re-growth scores are presented in Figure 29.

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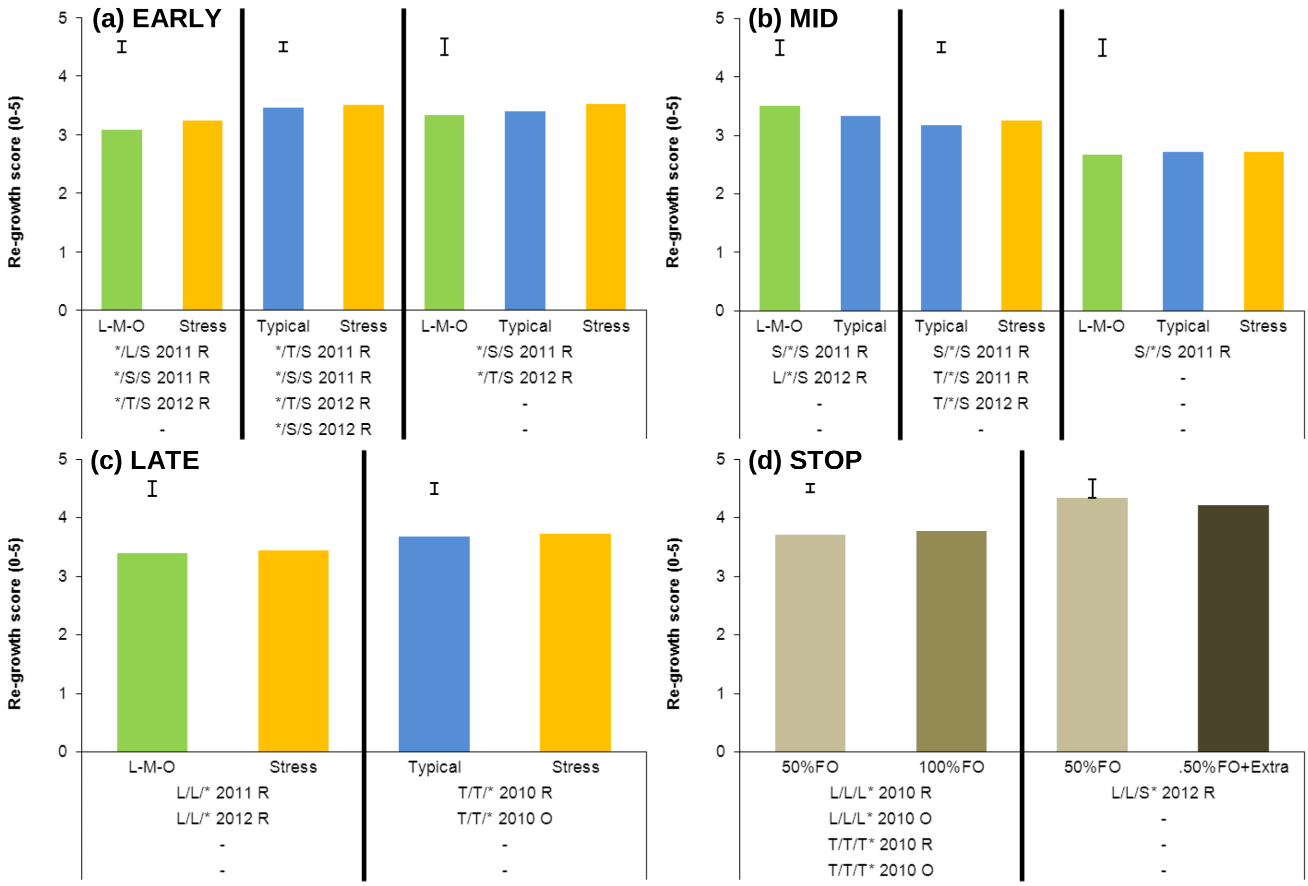

Figure 29 Bulb re-growth score as a result of irrigation regime during early season (a), mid-season (b), late season (c) and stop timing (d).

Bulb re-growth was not significantly affected by irrigation regime timing during the season or by irrigation stop timing, although there was a slight trend to suggest that more stressed regimes may slightly increase re-growth.

Post-storage dry matter content

Bulb post-storage dry matter content results are presented in Figure 30.

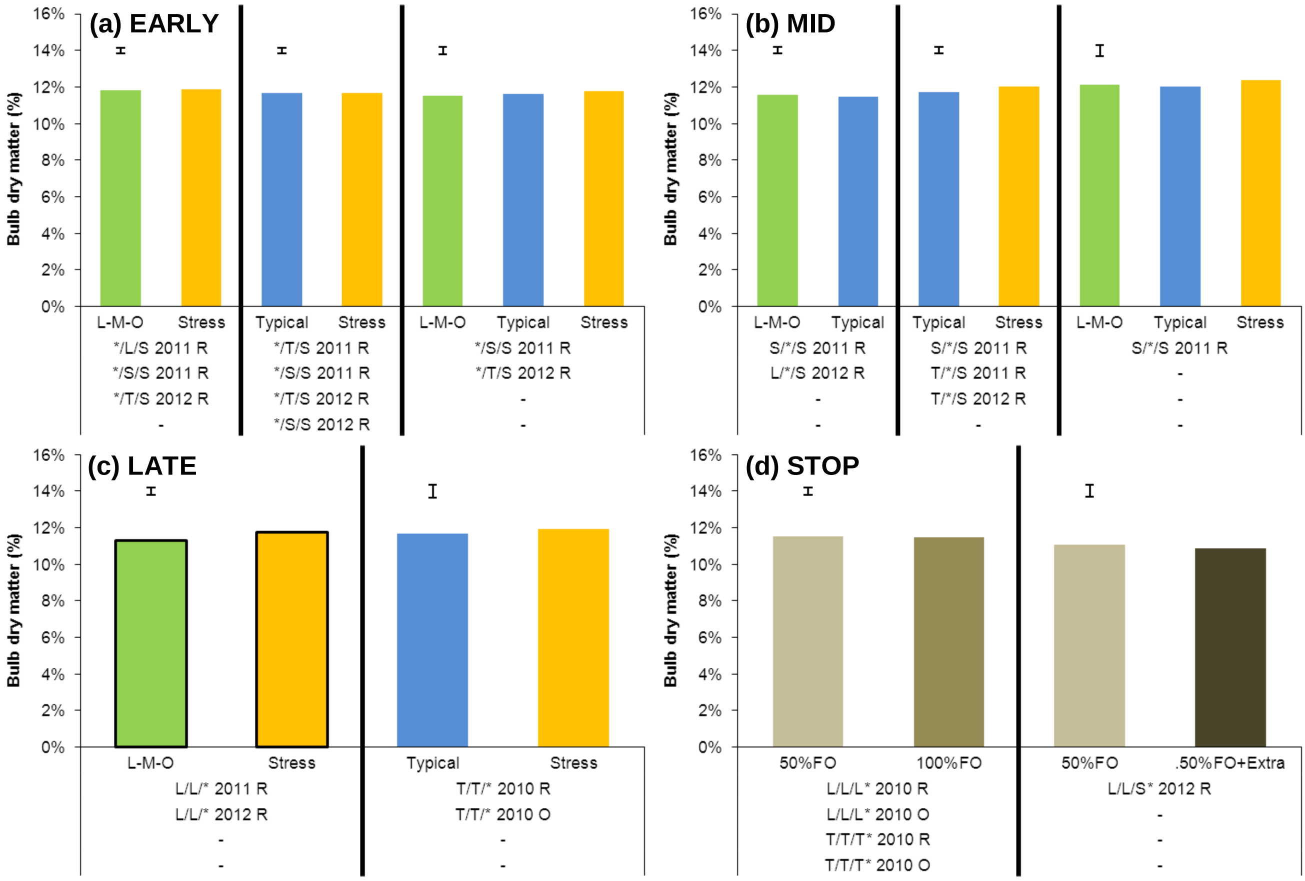

Figure 30 Bulb post-storage dry matter content as a result of irrigation regime during early season (a), mid-season (b), late season (c) and stop timing (d).

Bulb dry matter was significantly lower in treatments with late "L-M-O" irrigation compared to late stress. However, there were no significant differences as a result of any other timing or regime combination, despite a reasonably consistent trend to suggest that more frequent irrigation slightly reduced bulb dry matter content.

Foliar disease severity

The maximum observed downy mildew severity scores during the season are presented in Figure 31. Note that there were no significant differences in observations of *Botrtyis* leaf blight, *Cladosporium* leaf blotch, secondary bacterial infections or bacterial rots, consequently this data is not presented here.

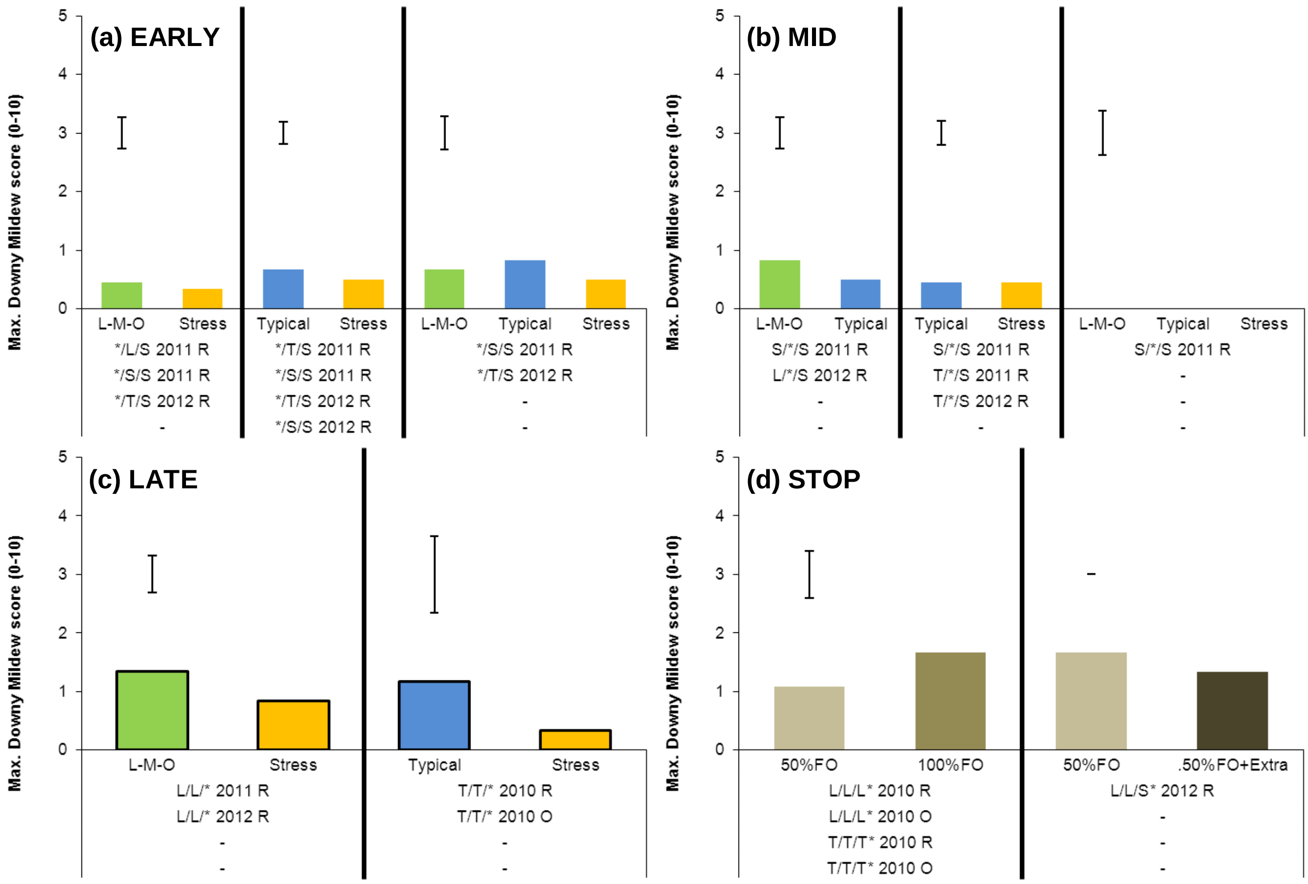

Figure 31 Maximum observed downy mildew severity score as a result of irrigation treatment during early season (a), mid-season (b), late season (c) and stop timing (d).

Irrigation regimes during early and mid-season and the stop time for irrigation had no significant effect on the maximum severity of downy mildew symptoms observed. However, either “L-M-O” or “typical” irrigation during the late season period (early August to stop irrigation) significantly increased downy mildew symptoms over “stress” irrigation. In general, there was a trend to suggest that greater levels of irrigation intensity increased downy mildew risk.

Thrip damage severity

Thrip damage severity scores are presented in Figure 32.

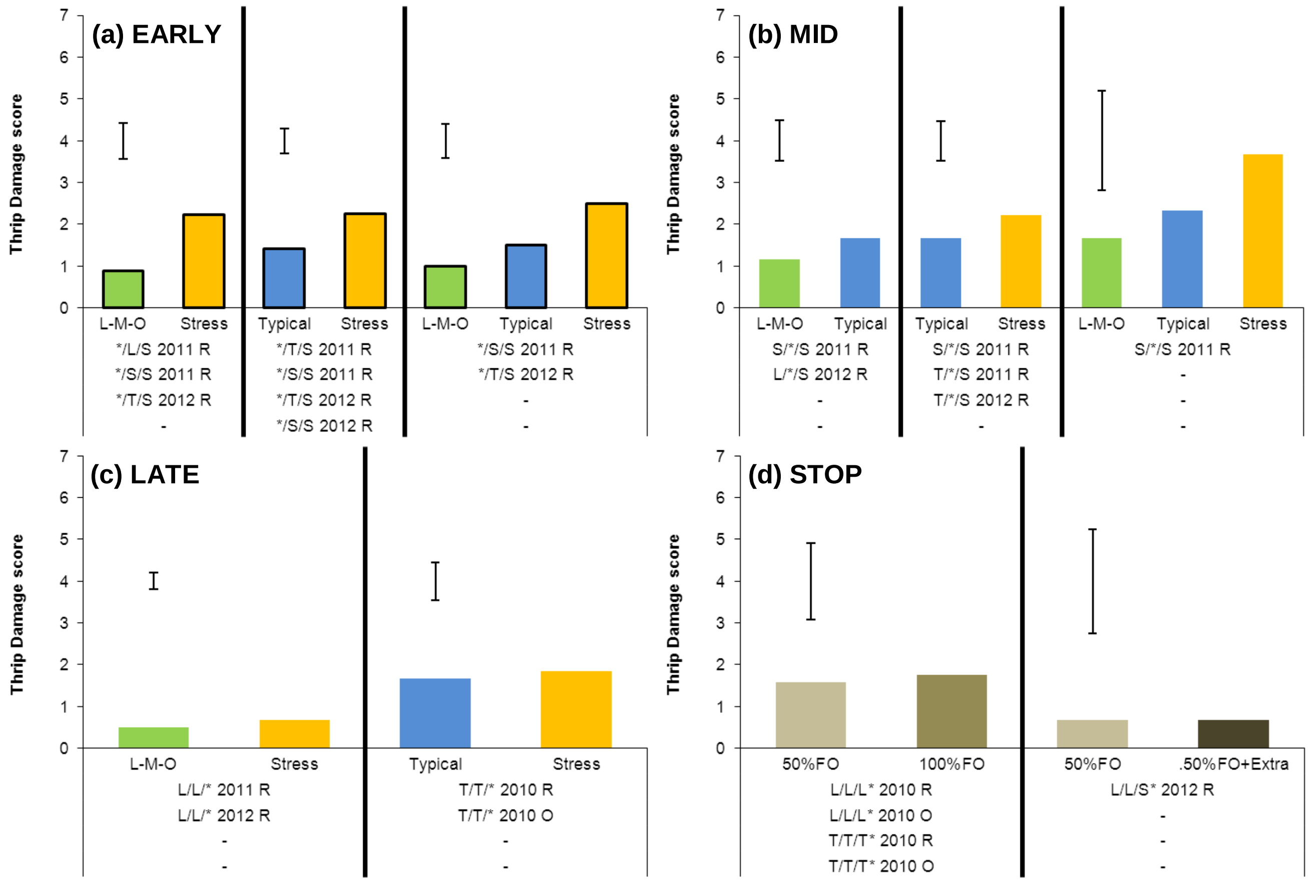

Figure 32 Thrip damage severity score as a result of irrigation treatment during early season (a), mid-season (b), late season (c) and stop timing (d).

Thrip damage was significantly reduced in treatments with either “L-M-O” or “typical” irrigation during early season when compared to “stress” irrigation. Although there were no significant differences in the severity of thrip damage as a result of the irrigation regime applied during mid or late season, or the irrigation stop time, there was a trend to indicate that less frequent irrigation increased thrip damage.

Weed levels

Weed levels at harvest are presented in Figure 33.

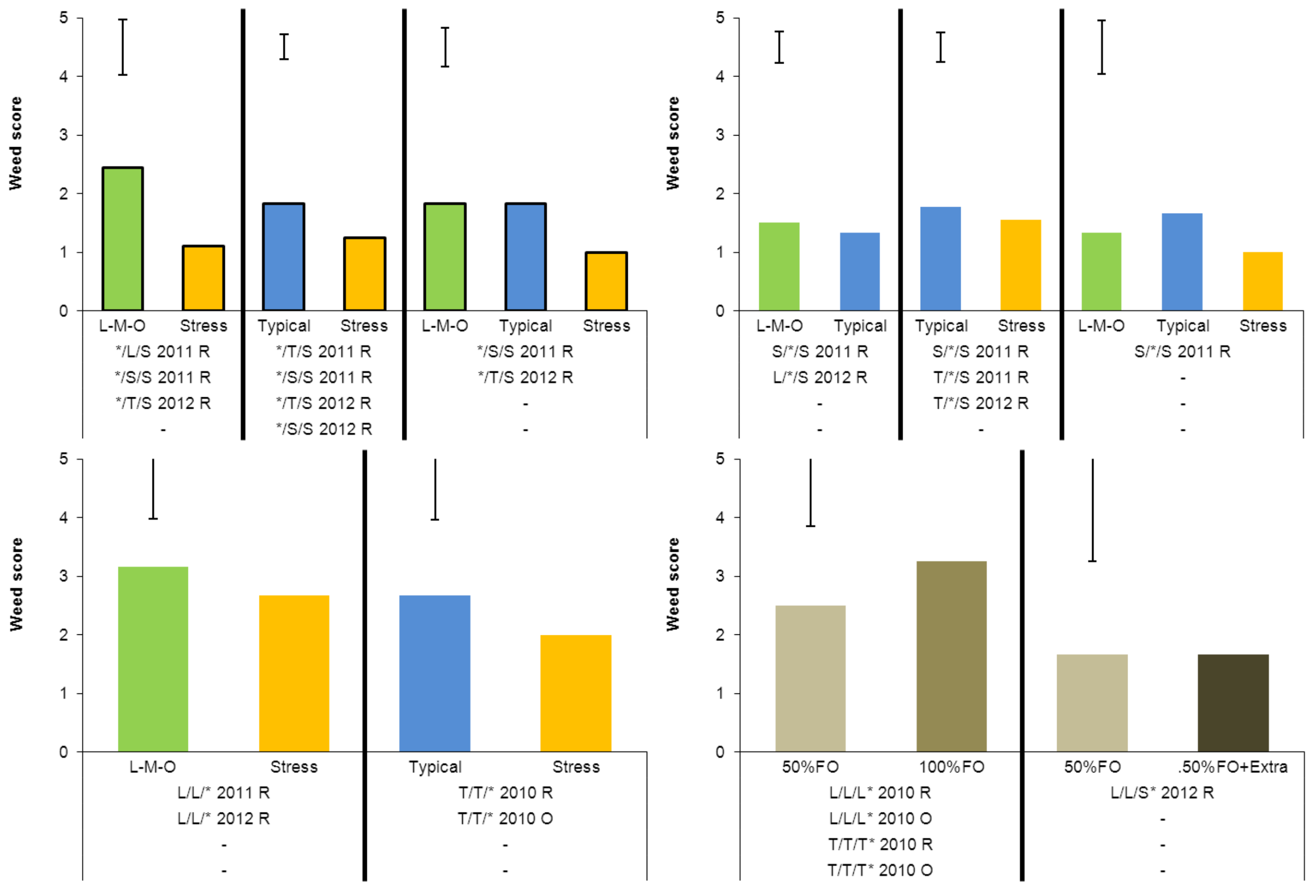

Figure 33 Weed level score as a result of irrigation treatment during early season (a), mid-season (b), late season (c) and stop timing (d).

Weed levels were generally higher in regimes with more frequent irrigations. However, this effect was only statistically significant where early season irrigation was considered, and there were no increases in weed levels between “L-M-O” and “typical” irrigation at this timing.

Soil nitrogen leaching

There were no significant differences in the relative change in ammonium (NH_4) and nitrate (NO_3) concentration within the 30-60cm profile as a result of any irrigation regime and timing combination. However, there was a slight trend to suggest that more frequent early season irrigation may slightly increase NH_4 and NO_3 at depth, indicating some potential for increased leaching, however, this was not supported by the mid or late season data. Figure 34 illustrates this data for the relative change in NO_3 concentration in the 30-60cm profile from the start to the end of the season.

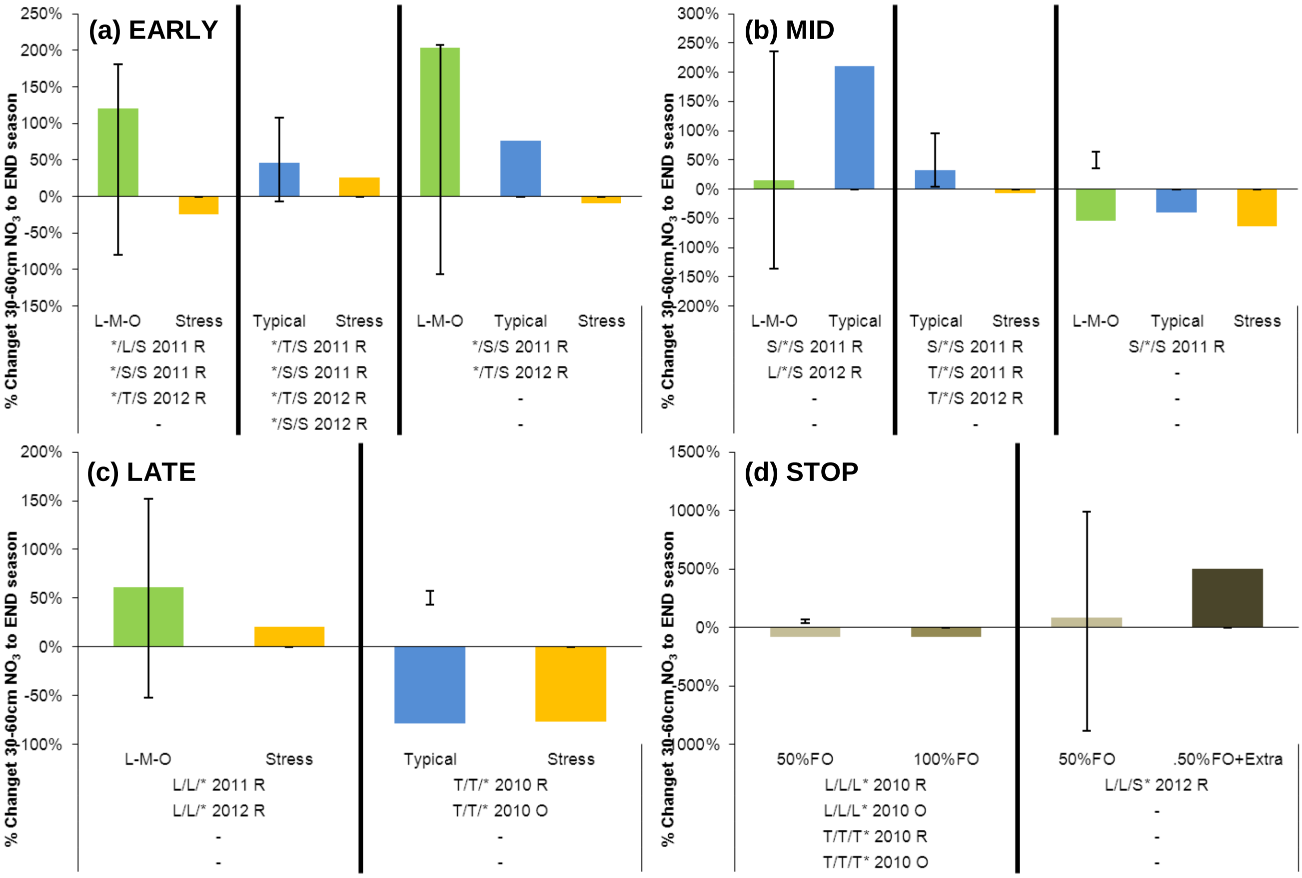

Figure 34. Relative change in NO_3 concentration at 30-60cm depth from start to end of season as a result of irrigation regime during early season (a), mid-season (b), late season (c) and stop timing (d).

Irrigation efficiency and cost-benefits

Irrigation efficiency

Figure 35 shows post-storage crop yield plotted against water received by the crop calculated using both measures A (all rain and irrigation) and B (rain and irrigation adjusted to account for potential losses before reaching the crop's roots) – see Methods section, page 16 for details. Note that this analysis includes data from both sites in all three trial years.

It was clear that there was an apparent threshold to further yield increase at around 270mm of received water using method A or 250mm of adjusted received water using method B. A linear regression was performed on the data below the apparent threshold, constrained through the origin (assuming that zero water would result in zero crop). The slope of this line represents the Water Use Efficiency (WUE). It was noted that there was an outlying data point relating to the non-irrigated treatment (N/N/N) on the open-field site in 2010, which had a low yield, despite an apparently large amount of water received. This anomaly largely relates to the timing of this water input – during the early and mid part of the season, there was relatively little rainfall, and the crop scarcely grew and senesced prematurely as a result of the drought stress. However, the late part of the season was much wetter – but the already senesced crop in the non-irrigated treatments was unable to make use of this water. The regression was repeated excluding this anomalous data point.

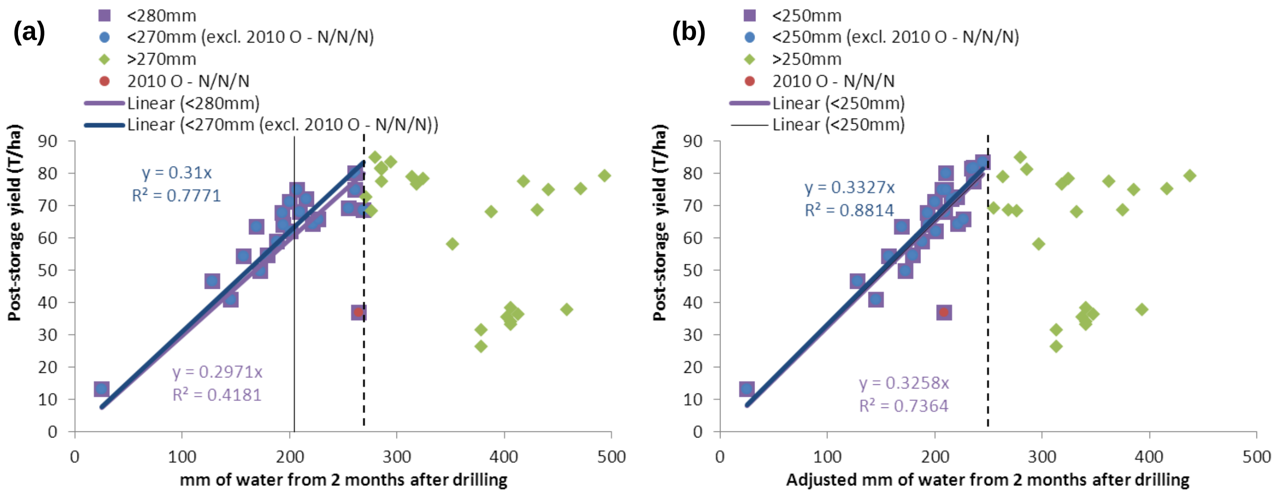

Figure 35 Correlation between total water received by the crop (a) and adjusted total water (b) and post-storage crop yield. Solid line indicates East Anglia mean rainfall May-Aug (inclusive) 1970-2012 (Met Office, 2013). Dashed line indicates threshold level.

There was a strong correlation between the depth of water received and crop yield up to the threshold level. This correlation was clearer when adjusted water (B) was considered compared to non-adjusted water received (A). The correlation was also considerably stronger when the outlying data point was removed.

The linear regressions indicated a WUE of around 0.30 T/ha/mm of total water received up to a maximum of around 270mm. This figure highlights the relatively low evapotranspiration demand in the UK: WUEs of less than half this are observed in more arid areas – e.g. 0.13 T/ha/mm in Texas, USA (Encisco *et al*, 2007).

Long-term average rainfall in East Anglia (1970-2013) was 203mm for the same period as analysed (effectively May to August inclusive). This indicates that irrigation could account for an additional average of 20.1 T/ha compared to rainfed production – equivalent to an additional gross return of around £3,400 per hectare, assuming an average value of around £170 per tonne after storage (based on Table 10). Note that this figure could be considerably larger, since it is likely that irrigated crops would have more of the higher value larger bulbs than non-irrigated production.

When adjusted water received was considered, the WUE was around 0.33 T/ha per mm of adjusted water received up to a maximum of around 250mm.

At levels of water input greater than the threshold value, both relationships start to degrade and appear to become somewhat negative.

<u>Cost-benefit</u>

Figure 36 presents gross farm gate returns against production costs for each irrigation regime at each site and in each of the three trial years.

It can be clearly seen that, despite the influence of seasonal weather patterns on crop production and the comparative benefit of different regimes, irrigation practices that overly stress the crop generally tend to be unprofitable (despite lower production costs), and more frequent “less-more-often” type treatments that continue later in the season tend to generate greater returns (but have greater production costs).

In order to further understand these relationships, the relative difference in net return from “typical” practice (i.e. T/T/S) in any given year was calculated, treating the rain-shelter and open-field site data separately (Figure 37).

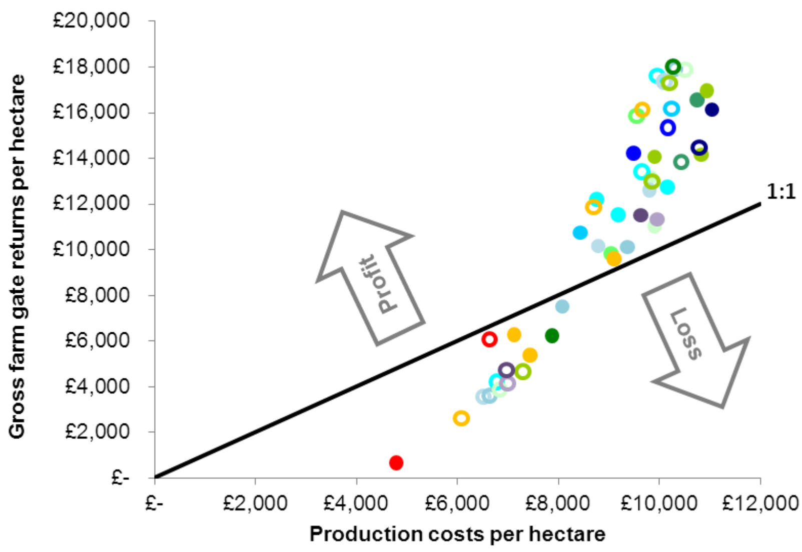

Figure 36 Gross farm gate returns versus crop production costs for each irrigation regime/year/site tested. Closed circles indicate data from the rain-shelter site and open circles indicate the open-field site. Colour relates to irrigation regimes in Table 8.

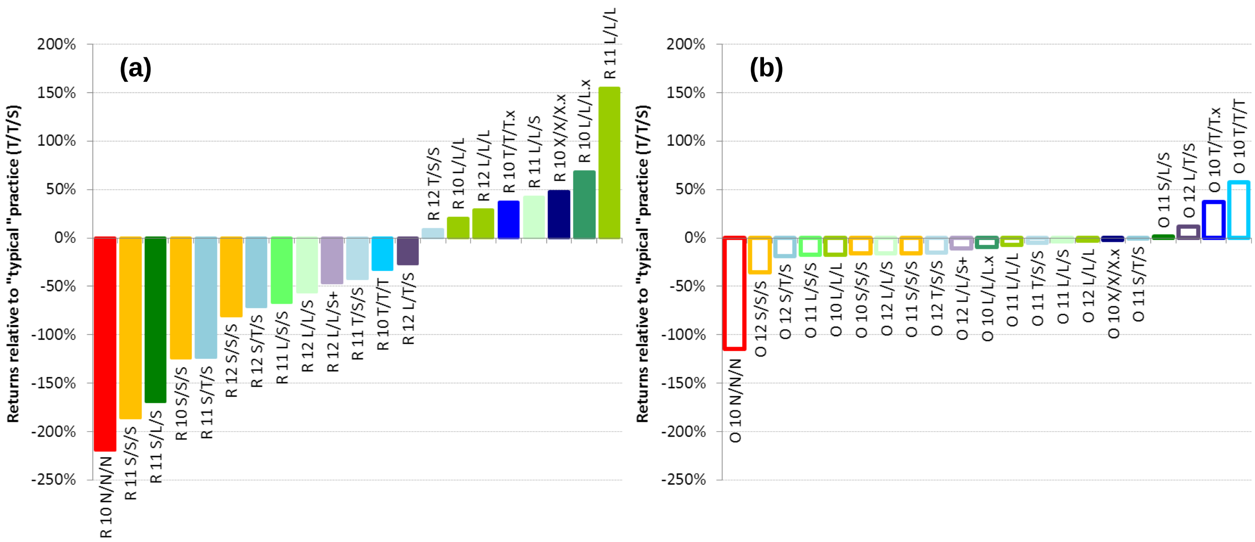

Figure 37 Net returns relative to "typical" practice (T/T/S) in the given year for the rain-shelter site (a) and open-field site (b). Colour relates to irrigation regimes in Table 8.

At the rain-shelter site (with no rainfall to supplement crop growth), it is clear that those regimes which introduced crop stress, considerably reduced returns by at least 50% and typically 75% to 150% when compared to "typical" practice. This effect was particularly pronounced when the stress period occurred during the early part of the season, and notably reduced the later in the season the stress period occurred. The greatest increases in return relative to “typical” practice (by at least 25% and typically up to around 70%) generally occurred where more frequent irrigations (either “L-M-O” or “excess”) were applied, and where irrigations continued latest in the season.

At the open-field site, there was less consistency in the data due to the wet seasons in 2011 and in particular 2012. Nevertheless, there was still a trend to indicate that stress, particularly during early and mid-season, reduced profits by between 15% and 35%, and later irrigation could help to increase relative returns by up to 50% in some cases. However, contrary to the rain-shelter site, more frequent “less-more-often” irrigations did not appear to add to profitability.

Discussion

Trials in 2010, 2011 and 2012 at both the rain-shelter and open-field site generated a significant amount of useful data to assist in understanding the impact of irrigation practices on bulb onion husbandry, quality and storability. However, due to the wet summers of 2011 and 2012, only data from the three trial seasons at the rain-shelter site and the 2010 season from the open-field site have been analysed in this final report.

Crop development, yield, quality, storability, disease/weeds levels and nitrate leaching

Data were analysed by blocks of comparable treatments to firstly allow investigation of the effect of "extreme", season-long irrigation regimes compared to "typical" irrigation and, secondly, to compare the effects of differing irrigation regimes during different parts of the season ("early", "mid", "late" and irrigation stop time). These data addressed objective 1 (parts a, b, c and d) and objective 2 (parts a, c and d) of the project.

The data indicated that there was no effect of irrigation regime on population at harvest – largely because crops were established to 2-3 true leaves before irrigation commenced.

Crop growth as percentage canopy cover and plant biomass was significantly greater with more frequent, "wetter" regimes through the whole season than "typical" irrigation, which in turn was greater than "stress" or no irrigation. Timing of application was important: although early season applications of "less-more-often" irrigation increased canopy cover and biomass through the mid-season over "typical" irrigation, by late season this disparity was no longer significant. Mid-season "L-M-O" did, however, significantly increase crop cover and biomass compared to "typical" by late season. "Stress" during early or mid-season significantly reduced canopy cover and biomass compared to "L-M-O" or "typical" irrigation. This finding supported previous work which identified the bulbing phase as the most sensitive to water stress (Bosch-Serra and Currah, 2002).

There were strong indications that fall-over timing was significantly later where crops were stressed during the early part of the season compared to either "typical" or "L-M-O" regimes – most likely as a result of greater foliage mass assisting fall-over in the non-stressed treatments. However, there were suggestions that late season "L-M-O" irrigation extended fall-over timing – probably indicating a return to foliage production from bulbing with additional water late in the season.

There were indications that "L-M-O" irrigation in early or late season (but not mid-season) significantly increased bolting compared to "stress" (but similar to "typical"). It is thought that the early season effect may be caused by crops being more forward as a result of early season irrigation when a climatic bolting inducing event (e.g. late frost) occurs, causing vernalisation and therefore bolting. However, it should be noted that bolting levels were variable from year to year and were all <1%, so results should be interpreted with caution.

"Stress" irrigation through the entire season significantly reduced post-storage crop yield and bulb size compared to "typical" or "L-M-O" (albeit that the latter was not significantly higher yielding than "typical"). "Excess" irrigation through the season significantly increased yields and bulb size compared to the "typical" regime. Again, timing was important: early season stress significantly reduced yields compared to "typical", but did not significantly affect bulb diameter, and; irrigating to 100% fall-over significantly increased both yield and bulb size. Although "wetter" mid-season irrigation regimes did not increase either yields or bulb diameter by a statistically significant amount, there were strong trends to suggest that there may have been some effect.

Contrary to field experience, there was no consistent evidence to suggest that more frequent irrigation regimes resulted in reduced bulb quality (with regard to post-storage diseases, internal disorders, skin quality or re-growth). Indeed, there were some indications that bacterial rots, internal doubles and regrowth may be increased by "stress" regimes. There were, however, indications that late season "L-M-O" irrigation could significantly reduce bulb dry matter content compared to the normal irrigation technique during this period ("stress").

Irrigation regime during the season had no effect on *Cladosporium* leaf blotch, bacterial rots or secondary bacterial infections. However, late-season "L-M-O" and "typical" irrigation both significantly increased the incidence of downy mildew. "Excess" irrigation and "L-M-O" through the whole season significantly increased downy mildew compared to "typical" and "stress" irrigation – most likely as a result of frequent irrigations late in the season. *Botrytis* leaf blight was also significantly increased by "excess" and "L-M-O" regimes compared to "stress", but showed similar levels of infection to "typical".

More frequent irrigation significantly reduced thrip damage compared to less frequent regimes ("stress" or no irrigation"). This effect was particularly noted during early season, although a similar but not statistically significant trend continued through the whole season.

Weed levels at harvest were slightly inconsistent, but were generally higher under more frequent irrigation, particularly where this occurred during the early part of the season when canopy cover was less.

The effect of irrigation regimes on soil ammonium and nitrate leaching were inconsistent throughout the trial, perhaps due to the highly variable nature of soil N measurements. Contrary to expectations, there were some indications from the whole-season data to suggest that more frequent irrigation through the whole season could reduce rather than increase leaching. It is suggested that this may be a result of increased crop growth under the “wetter” regimes, perhaps allowing greater usage of soil nitrogen at depth especially when the soil lay permanently damp, thereby allowing easier extraction of nutrients. This trend was contradicted by indications that greater early season irrigation may slightly increase nitrate leaching from the 0-30cm profile to the 30-60cm depth.

Irrigation efficiency and cost-benefits

All trial data (including the previously excluded data from 2011 and 2012 at the open-field site) was evaluated to determine irrigation efficiency and cost-benefit of the regimes. This analysis addressed objective 2 b and helped to contribute to objective 3 of the project.

Analysis of post-storage marketable yield compared to irrigation and/or rainfall input during the main growing season (2 months after drilling until harvest) indicated strong relationships up to a threshold point where further irrigation produced no more yield and the relationship started to degrade. It is suggested that some of the relationship breakdown at high water input levels may relate to reduced crop growth as a result of the lower light levels which corresponded with increased rainfall input.

When total water inputs were considered, yields increased at around 0.30 T/ha per mm of water applied up to a total of 270mm. Given that long-term average rainfall during the main growing season in East Anglia is around 203mm (Met Office, 2013), the losses caused by not irrigating would be an average of around £3,400 per hectare in gross returns compared to fully irrigated crops (assuming £170 per tonne for cured and stored onions). Naturally, yields and prices could vary significantly from season to season, particularly when bulb size is considered, so the range of risk presented by not irrigating could be significant. With typical production costs at around £3,250 without irrigation or storage costs (VCS, 2013a), it is clear that irrigation is a critical element of current production systems, and they would not be profitable without it.

Adjusting the water inputs to account for evaporative and run-off losses indicated that further yield increase ceases at around 250mm water received. This corresponds well with field estimates of onion crop water use (evapotranspiration, ET_c) for the period under consideration. This is typically estimated at <0.25mm/day in April after emergence, rising slowly at first in line with canopy development, then increasingly rapidly to an average of around 3.5mm/day in late July, before falling quite rapidly from mid-August as the crop matures (VCS, 2013b). For the period from around mid-May to harvest, this estimated water use typically totals around 260mm. Similar relationships have been identified in previous work, indicating that irrigation of around 100-120% of ET_c gave maximum yields (i.e. total water input of 250-300mm in the UK from mid-May to harvest) (Brewster, 2008).

It is worth noting that significant periods during the trial years (and especially during 2011 and 2012) were more overcast than normal. Since onion crop growth is largely driven by light levels, it is highly likely that solar radiation was a limiting factor in these years. Therefore the threshold of water inputs before onion yields cease to increase could be higher in brighter seasons.

Looking into cost-benefits in more detail, it was clear that although "little and often" type and late-season irrigation were considerably more costly, the resulting increases in yields and size grades (which were not necessarily statistically significant when considered separately) combined to considerably increase net returns when compared to "typical" irrigation practice. However, this effect was only apparent in the rain-shelter trial (effectively replicating an extremely dry season), where "little and often" type regimes increased profitability by at least 50% over "typical" practice. Under open-field irrigation, where a little (or in 2011 and 2012, quite a lot of) rainfall supplemented irrigation, the benefits of "little and often" were not apparent, generally resulting in losses of 2-17% when compared to "typical" practice. It is thought that some of this difference may be caused by slower crop growth in wet seasons in open ground cultivation, limiting the potential to achieve the high crop yields required to justify the additional irrigation costs of "little and often" practices. In addition, there may be some effect of the reduced ability of the soil to capture rainfall when it is kept constantly moist. Instead, it was late-season irrigation and irrigation after 50% fall-over that tended to out-perform the net returns of "typical" irrigation practice – generally by around 50% increase. However, as indicated earlier, such late-season irrigation practices are not usually to be recommended unless significant dry periods are forecast.

Identifying optimal irrigation regimes

Based on the analysis of the crop data and cost/benefits above, it is clear that under-irrigating is detrimental to onion production, particularly during the early part of the season. It is also clear that irrigating "little and often" during the early and mid-season can increase marketable yields and profitability in dry seasons, but can be considerably less profitable in wetter seasons than "typical" practice. "Little and often" practices were also implicated in increased weed levels and bolting risk (if applied early in the season). Late season irrigation, particularly if "little and often", was implicated in increased foliar disease, lower bulb dry matter and delayed crop maturity.

Given that long-term rainfall forecasts are, at best unreliable, it would seem prudent to strike a balance between expensive, time-consuming and more risky "little and often" irrigation or late season irrigation practices and their potential benefits. This exact nature of this balance will, to some extent, depend on the "droughtiness" of the season.

On this basis, the irrigation regime in Table 12 is suggested as a reasonable and practical balance between achieving optimum crop yield and quality while minimising agronomic and financial risk.

Note that Table 12 has been generated with the assumption that weather conditions are predicted to remain dry for a period after irrigation has commenced. Consideration of forecast rain should always be given when programming irrigation in order to minimise the risks of drainage (and wasted irrigation effort/cost) by irrigating soil to field capacity when wet conditions are imminently forecast. Adjustments to application depths could be made to account for predicted rainfall if required.

Table 12 Suggested optimum irrigation regime for bulb onions (for sandy loam / loamy sand). Note that suggested applications are subject to individual soil characteristics and consideration should be given to forecast rain before scheduling applications.

Crop growth stage	ESTABLISHMENT Drilling to 2-3TL			EARLY SEASON 2-3TL to bulb initiation			MID SEASON Initiation to "egg" stage			LATE SEASON "Egg" stage to stop			STOP TIME		
Comment	If sufficient moisture in seed bed, irrigation only required under very dry conditions to aid establishment and pre-emergence herbicide activity.			Early season irrigation is important, becoming critical during particularly dry periods.			Mid season irrigation is critical to build crop biomass and promote bulb growth, becoming less important only under wet conditions.			During late season, controlled moisture stress should be allowed to develop to help promote bulbing and crop maturity. In particularly dry periods, more frequent irrigation will increase yields.			Under most circumstances, stop irrigation at 50% canopy fall-over. In particularly dry periods, irrigation up to 100% fall over will increase yields but should limit associated disease and quality risks.		
Weather	Dry	Normal	Wet	Dry	Normal	Wet	Dry	Normal	Wet	Dry	Normal	Wet	Dry	Normal	Wet
Importance of irrigation during period	Medium	Low	Low	High	Medium	Medium	High	High	Medium	Medium	Low	Low	Low	Low	Low
Description of irrigation trigger point and application	Low dose to minimise capping and cool shock potential.	Unlikely to be required	Not required	Return soil to FC when SMD reaches 25% of AWC	Return soil to FC when SMD reaches 50% of AWC	Return soil to FC when SMD reaches 50% of AWC	Return soil to FC when SMD reaches 25% of AWC	Return soil to FC when SMD reaches 25% of AWC	Return soil to FC when SMD reaches 50% of AWC	Return soil to FC when SMD reaches 50% of AWC	Apply approx. 50% of AWC when SMD reaches 75% of AWC	Apply approx. 50% of AWC when SMD reaches 75% of AWC	Stop at **50%** fall-over In extremes, further irrigation could be applied.	Stop at **50%** fall-over	Stop at **50%** fall-over
Estimated application for: **Loamy sand** (~35mm root zone AWC)	<10mm	-	-	12mm at 10mm SMD	20mm at 18mm SMD	20mm at 18mm SMD	12mm at 10mm SMD	12mm at 10mm SMD	20mm at 18mm SMD	20mm at 18mm SMD	20mm at 26mm SMD	20mm at 26mm SMD	20mm at 26mm SMD	-	-
Estimated application for: **Sandy loam** (~45mm root zone AWC)	<15mm	-	-	15mm at 12mm SMD	25mm at 23mm SMD	25mm at 23mm SMD	15mm at 12mm SMD	15mm at 12mm SMD	25mm at 23mm SMD	25mm at 23mm SMD	25mm at 34mm SMD	25mm at 34mm SMD	25mm at 34mm SMD	-	-

Green text indicates "little and often" practice; Blue indicates "typical" practice, Orange indicates "stress" regimes
FC = Field Capacity; SMD = Soil Moisture Deficit; AWC = Available Water Content

Conclusion

This three year project has successfully generated significant quantities of data in order to achieve its aim of investigating the impact of irrigation practices on Rijnsburger bulb onion husbandry, yield, quality and storability while also considering the more general impacts on water, nutrient and pesticide resources.

Overall, the results indicated that “little and often” irrigation applied during the early part of the season (to bulb initiation), and particularly during the middle part of the season (from initiation to “egg” stage) significantly increased crop development and reduced thrip damage risks when compared to “typical” irrigation. However, although such practices led to some yield and bulb diameter increases, these were not always statistically significant when compared to “typical” irrigation. Echoing this, cost-benefit analysis indicated that “little and often” irrigation would be considerably more profitable by at least 50% in drier seasons but less profitable by up to 17% in wetter seasons when compared to “typical” practice.

Late season irrigation after “egg” stage until irrigation stop (usually at 50% fall-over) and irrigation beyond 50% fall-over also significantly increased bulb yield and size compared to the normal practice of inducing stress during the late season and stopping irrigation at 50% fall-over. Cost-benefit analysis again reflected this data, suggesting that late season irrigations could increase profitability typically by around 50%.

However, the potential benefits of “little and often” practices and late season irrigation need to be balanced against the risks. There was evidence that more frequent irrigation could increase weed levels and the risk of bolting when excess foliage development occurs early in the season. More frequent irrigation during the late season period increased foliar disease levels (especially downy mildew), delayed canopy fall-over and reduced bulb dry matter content. Furthermore, late irrigation could potentially jeopardise harvesting operations if further rainfall is received.

It is therefore recommended that “little and often” practices during early season should only be pursued when conditions are particularly dry. During mid-season, the benefits of “little and often” tend to be more pronounced, and it is recommended that this practice is pursued where possible during dry and “normal” weather conditions. However, it is not recommended to pursue a late irrigation strategy in an attempt to gain yield because of the increased risk of lower quality bulbs and delayed maturity, unless prolonged dry weather is forecast during the late season period.

Irrigation practices that maintain a level of controlled water stress during the season were detrimental to crop yield and to a lesser degree bulb size – again with the period up to bulb initiation being highlighted as critical. There were also indications that water stressed crops may result in increased bulb diseases, internal disorders and perhaps also greater re-growth during storage. Cost-benefit analysis suggested that even limited stress conditions such as imposed during this project could reduce profitability by up to 150% in dry conditions.

Analysis of crop response to water inputs indicated that relying solely on rainfall to grow onion crops in the current main production area of East Anglia would reduce gross farm returns by an average of around £3,400 per hectare (equivalent to 20 tonnes of yield) when compared to “typical” irrigation practice. This figure would most likely be higher if the impact on bulb sizes were accounted for. This would effectively result in long-term net profits of little more than zero for rain-fed onion production, highlighting the critical importance of irrigation to the industry.

“Best practice” guidelines, based on the recommendations from this project will be summarised in an industry fact-sheet, to be published by the HDC following this report.

Knowledge and Technology Transfer

- Short article highlighting the start of FV 326a project for Vegetable Consultancy Services Root Grower newsletter, June 2010. Note: the VCS newsletter is circulated to around 40 onion growers totalling approximately 50% of the UK onion area.
- Review article for HDC Field Vegetable Review 2011
- Summary article HDC News June 2011
- Field day at Broom's Barn Research Centre – 28th June 2011, including local radio interview.
- Review article for HDC Field Vegetable Review 2012
- Short summary article for Vegetable Consultancy Services Root Vegetable Grower newsletter (March 2012).
- Summary article and interim irrigation guidance for Vegetable Consultancy Services Root Vegetable Grower newsletter (July 2013).
- Throughout the project, there has been extensive data sharing and collaboration with LINK project HL0196 "Developing precision irrigation for field-scale vegetable production, linking in-field moisture sensing, wireless networks and variable rate application technology". This data was used to assist the project to validate onion growth and water response models.
- "Best practice" guidelines, based on the recommendations from this project will be summarised in an industry fact-sheet, to be published by the HDC following this report.

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Appendices

Appendix 1 – treatment regimes grouped over 2010, 2011 and 2012

Open-field	Rain-shelter			Code	Old Trt	Name	L May to Initiation (E July)		Initiation (E Jul) to egg stage (E Aug)		Egg stage (E Aug) to Stop		Stop
2010	2010	2011	2012				Trigger	Target App^n	Trigger	Target App^n	Trigger	Target App^n	
1 yr		3 yrs		T/T/S	2010/11/12 A	Typical	50% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
1 yr	1 yr			T/T/T	2010 B	Typical, no extra stress	50% AWC	Return to FC	50% AWC	Return to FC	50% AWC	Return to FC	50% FO
1 yr	1 yr			T/T/T.x	2010 C	Typical, no extra stress, extended	50% AWC	Return to FC	50% AWC	Return to FC	50% AWC	Return to FC	100% FO + 50% dead
		2 yrs		T/S/S	2011/12 B	Typical with mid+end season stress	50% AWC	Return to FC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
		2 yrs		S/T/S	2011/12 C	Typical with early+end season stress	75% AWC	50% of AWC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
1 yr		3 yrs		L/L/L	2010/11/12 D	Less more often, no extra stress	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	50% FO
1 yr	1 yr			L/L/L.x	2010 E	Less more often, no extra stress, extended	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	100% FO + 50% dead
		2 yrs		L/L/S	2011/12 E	Less more often, end season stress	25% AWC	Return to FC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
		1 yr		L/S/S	2011 F	Less more often, mid+end season stress	25% AWC	Return to FC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
		1 yr		S/L/S	2011 G	Less more often, early+end season stress	75% AWC	50% of AWC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
			1 yr	L/L/S+	2012 F	Less more often, end season stress irrigation at 100% FO	25% AWC	Return to FC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO but 10mm @ 2 days before harvest
			1 yr	L/T/S	2012 G	Less more often, typical mid season, end season stress	25% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
1 yr	1 yr			X/X/X.x	2010 F	Excess	12.5% AWC	Return to FC	12.5% AWC	Return to FC	12.5% AWC	Return to FC	100% FO + 50% dead
1 yr		3 yrs		S/S/S	2010 G 2011/12 H	Stress	75% AWC	50% of AWC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
1 yr	1 yr			N/N/N	2010 H	No irrigation	-		-		-		-