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**MODELLING THE IMPACTS OF IN-FIELD
SOIL AND IRRIGATION VARIABILITY ON
ONION YIELD**

SCHOOL OF APPLIED SCIENCE

MPhil

Supervisor: **Dr Jerry W Knox, Dr Tim Hess**
November, 2013

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8th November 2013

Initial registration: 24th October 2011

TABLE OF CONTENTS

TABLE OF CONTENTS	i
ABSTRACT	v
ACKNOWLEDGEMENTS.....	vii
LIST OF FIGURES.....	ix
LIST OF TABLES	xi
LIST OF ABBREVIATIONS	xiii
Chapter 1. Introduction	1
1.1 Background.....	1
1.2 Aim and objectives.....	3
1.3 Thesis structure	4
Chapter 2. Water relations and irrigation requirements of onion (<i>Allium cepa L.</i>): A review of yield and quality impacts.....	7
Summary	7
2.1 Introduction	8
2.2 Centres of production.....	9
2.3 Crop development.....	10
Transplant/emergence.....	12
Canopy formation/vegetative growth	13
Bulb initiation	13
Bulb/yield formation	13
Fall-over and bulb ripening	14
Onion seed production.....	14
Summary	14
2.4 Roots	15
2.5 Plant water relations	15
Summary	16
2.6 Soil water measurements	16
Soil water content and soil water potential.....	16
Field capacity.....	17
Field Capacity determination	18
Permanent wilting point	18
Soil water release curves.....	19
2.7 Crop water requirements	20
K _c estimation.....	20
Seasonal water requirements	21
Summary	23
2.8 Yield and quality response to water	24
Summary	26
2.9 Irrigation systems.....	27
Furrow irrigation.....	28

Overhead irrigation	29
Drip irrigation	29
Summary	30
2.10 Irrigation scheduling	30
In-situ soil moisture measurement	32
Simulation models	32
Irrigation scheduling services	32
Deficit irrigation	32
Irrigation scheduling constraints	33
Summary	34
2.11 Drivers for change	34
2.12 Conclusions	35
Lopez-Urrea <i>et al.</i>	37
Chapter 3. Current trends and management practices in UK onion production - an industry survey	39
3.1 Introduction	39
3.2 Methodology	39
3.2.1 Identifying target areas for survey	39
3.2.2 Identifying the key attributes of onion production	42
3.2.3 Produce questionnaire	43
3.2.4 Conducting the interviews	43
3.2.5 Survey outputs	44
3.3 Results	45
3.3.1 Crop and soil management	45
3.3.2 Irrigation and fertiliser management	51
3.3.3 Yield and quality	53
Marketable production	53
Yield: average production and variability	54
Water and soil effects on yield	55
Quality	56
Factors affecting quality	57
Chapter 4. AquaCrop - model parameterisation for onion (<i>Allium cepa</i> L.) cv Arthur 59	
4.1 Introduction	59
4.2 Methodology	60
4.2.1 Experimental outline and crop data collection	62
Study site	63
Climate data collection	64
Soil data	65
Soil water data collection	66
Crop data collection	66
4.2.2 Model description	67

4.2.2.1 Model calibration.....	72
4.2.2.2 Model validation.....	72
4.3 Results and discussion	74
Chapter 5. AquaCrop - model parameterisation for onion (<i>Allium cepa</i> L.) cv Arthur 85	
5.1 Introduction	85
5.2 Methodology	88
5.2.1 Defining model scenario.....	89
Climatic conditions: 5 different years	89
Soils: 2 different soils.....	93
Cropping practices.....	93
Uniform irrigation	95
Non-uniform irrigation	96
5.2.2 Assessing statistical differences between soils, years, and irrigation systems	98
5.3 Results and discussion	99
Uniform irrigation.....	99
Non-uniform irrigation.....	101
Chapter 6. Discussion and implications of research	112
6.1 Implications for science and research.....	112
6.2 Implications for the industry	114
6.3 Methodological limitations.....	115
6.4 Recommendations for growers	117
6.5 Future research	118
6.6 Challenges facing future UK onion production.....	118
Chapter 7: Conclusions	120
Chapter 8: References	123
APPENDICES	143
Appendix A : UK onion survey: Questionnaires	143
A.1 Questionnaire 1: Questionnaire targeting GROWERS....	143
A.2 Questionnaire 2: Questionnaire targeting AGRONOMISTS	148
A.3 Questionnaire 3 Questionnaire targeting INDUSTRY	153
A.4 Case study: yield variability onion yield in Elveden	156
Appendix B : Crop growth model identification	157
B.1 Single crop models for onion.....	157
B.2 Multiple-crop models	158
B.3 Model Identification	162
Appendix C : Data for model calibration.....	166
C.1 Irrigation treatments in Broom’s Barn Research Centre..	166
C.2 Irrigation trials’ plot’s layout in Broom’s Barn Research Centre.....	168
C.3 Onion DM determination.....	169
Appendix D : AquaCrop parameters	170

D.1 Crop parameters	170
D.2 Simulated and observed CC and SMC values for 2010, 2011 and 2012	173
Appendix E Irrigation Evaluation	175
E.1 Boom.....	175
E.2 Linear move	177
Appendix F : Weather data	179
F.1 Very wet year	179
F.2 Average wet year	179
F.3 Average year.....	180
F.4 Average dry year	180
F.5 Very dry year.....	181
F.6 Reference irrigation schedule.....	182
Appendix G : Statistical Analysis.....	184
G.1 Study of the distribution of the residual values	184
G.2 Results of Kruskal-Wallis test	185

ABSTRACT

Globally, onion (*Allium cepa* L.) represents an extremely important crop in terms of production, value and consumption. Similarly, in the UK onion production is considered to be one of the most important high-value field vegetables, with ca. 300,900 tonnes being produced from 8,448 ha (DEFRA 2010). However, a great variability in onion productivity (yield) has been identified due to a combination of environmental, genotypic, management and agronomic factors. The increasing demand for high quality vegetables and their supply year round is adding significant pressure on farming enterprises, which add to the challenges UK onion producers already face (e.g. crop management, irrigation and pest control decision-making).

The aim of this research was to assess the impacts of in-field soil and irrigation variability on onion yield and quality. Therefore, the scientific evidence on the relationships between onion yield, crop water use, irrigation and crop quality were initially reviewed and the evidence corroborated with data from an industry survey. In order to evaluate the effects of soils and irrigation variability on yield, under different agroclimatic conditions, a crop growth model (AquaCrop) was calibrated and then validated using experimental field data. The scientific evidence in the literature and results from the industry survey were used to validate and calibrate the AquaCrop model for brown onion (*cv Arthur*). Statistical analyses were used to assess crop model goodness of fit. A series of scenarios were then defined and the AquaCrop model used to assess the impacts of different onion cropping practices, production areas and typical and extreme climatic conditions on crop yield.

The effects of irrigation non-uniformity (typical of a boom and linear move irrigation application system) on production were assessed under a series of agroclimatic conditions (five different years) and two contrasting soil types (sandy and sandy loam). The simulations showed that the lowest yield (8.6 t DM/ha) and greatest variability (standard deviation: 0.23 t DM/ha) occurred under the driest agroclimatic conditions. Production on sandy soils resulted in higher yield (in average 0.24t DM/ha) than on a sandy loam soil. The yield

under hoses fitted with booms were statistically significant (Kruskal-Wallis analysis) lower than for the linear move, although the difference was very small (average of 9.52 t DM/ha vs. 9.56 t DM/ha). Under 'average dry' conditions, the highest yield was produced on sandy soils (8.78 t DM/ha), contrary to 'average' agroclimatic conditions, where the highest yield was produced on sandy loam soils (9.55 t DM/ha). For the driest season, the effects of irrigation variability were only significant on sandy soils (8.80 t DM/ha and 8.73 t DM/ha for hose fitted with linear move and boom, respectively). The study of uniform versus non-uniform irrigation applications showed that onion yield was higher under uniform irrigation. The differences between yields produced under uniform and non-uniform irrigation increased with increasing climatic aridity (0.01-0.18 t DM/ha compared to average values). Differences were greater in cases of boom application systems. Onion yield generated by simulations of uniform conditions fell within the range found in the literature. The variability observed under non-uniform irrigation was the same (up to 30-40%) as the overall variation reported by growers.

Keywords: onion, yield, irrigation, uniformity

ACKNOWLEDGEMENTS

I would like to thank Dr Jerry Knox in his role as primary thesis supervisor for his guidance, support and encouragement throughout this time; Dr Tim Hess in his role as secondary thesis supervisor for his ideas and technical knowledge on modelling; and Dr Andre Daccache for his assistance, enthusiasm and advice.

I would also like to acknowledge Defra Hortlink for funding this research.

Thanks also to all the growers and industry members for their active engagement with the project and for sharing their valuable time and priceless experience. A special thanks to Dr Tim Lacey and Tom Will, whose work and patience have been of precious guidance for this work.

Thank you from the bottom of my heart to my family and friends whose support and love in the distance have made this possible.

I would like to acknowledge all those faithful members of our Fridays' 'at the farm dinners' and Tuesdays' special 'Pie Nights', for the good times shared and the bad times combatted.

Finally, to all those who have made of my Cranfield experience a lifetime opportunity, thank you.

LIST OF FIGURES

Figure 1 The relation between water content (m^3/m^3) and suction (kPa) for a sand and a loam soil (moisire characteristic curves). Marshall et al. (1976), p. 33.....	19
Figure 2 Regional production of outdoor field vegetables based on EDINA and DEFRA (2010) in the England and Wales in 2010	41
Figure 3 Classification of England and Wales soils by their texture (Source: National Soil Research Institute)	41
Figure 4 Spatial variability in agroclimate ($PSMD_{max}$) for the UKCP09 long-term average baseline (1961-90) in England and Wales.....	41
Figure 5 Typical onion planting layout: bed centres 1.83 m apart with 4 rows of plants	48
Figure 6 Typical development stages for an onion crop in the UK (pers comm, 2013).....	49
Figure 7 Irrigation by linear move on a red onion cv <i>Red Baron</i> field on a commercial farm, Elveden Estate (Norfolk), August 2012.....	51
Figure 8 Growers' reported and targeted onion size range (mm) and proportion (%).	54
Figure 9 Mean monthly rainfall and ETo (mm) and average temperature ($^{\circ}C$) recorded in Broom's Barn Research Centre in 2010, 2011 and 2012 under the polytunnel.....	64
Figure 10 Chart of AquaCrop indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield [I, irrigation; Tn, minimum air temperature; Tx, Max air temperature; ETo, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; gs, stomatal conductance; WP, water productivity; HI, harvest index; CO ₂ , atmospheric carbon dioxide concentration; (1), (2), (3), (4), different water stress response functions]. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. (Steduto <i>et al.</i> , 2009).....	69
Figure 11 Schematic outline of the AquaCrop model operation (Raes <i>et al.</i> 2011).....	70
Figure 12 AquaCrop model simulated and observed soil moisture content (mm) in the root zone in the plots under irrigation treatments A and B in 2010 for the months May (5) to September (9).	79

Figure 13 AquaCrop simulated and observed canopy cover (CC) for the given days after planting (DAP) selected in irrigation regimes (A and B) in 2010 at Brooms Barn.	80
Figure 14 AquaCrop observed and simulated onion yield (t of DM per ha) and total irrigation depth for the different irrigation regimes in Brooms Barn experimental station in 2010, 2011, and 2012. Error bars show maximum and minimum observations.	80
Figure 15 Linear correlation of simulated against observed yield (t/ha) for the irrigation treatments included in the AquaCrop model calibration and validation	82
Figure 16 Hosereel fitted with a boom (upper photo) and linear move (lower photo) irrigation application systems on onions, Elveden (2012).	87
Figure 17 Ranked PSMD _{max} for the locations (Bedfordshire, Cambridgeshire, Norfolk, Suffolk, and Lincolnshire) for the years 1961-2011.....	92
Figure 18 Schematic outline of the AquaCrop scenario modelling including input files and scenarios used to assess the impacts of soil, climate and irrigation equipment on onion yield.	94
Figure 19 Histogram showing the average variability in irrigation deviation (%) occurring in boom and linear move irrigation application methods.....	97
Figure 20 AquaCrop simulated onion yield (t ha ⁻¹) for five contrasting years (A: very wet, B: average wet, C: average, D: average dry, and E: very dry) on two soil types (sand and sandy loam), under two different irrigation systems (a hosereel with boom and a linear move).	102
Figure 21 Schematic representation of a normal distribution around a mean μ , with a given standard deviation σ	103
Figure 22 Simulated onion yield (t DM ha ⁻¹) under uniform and non-uniform (boom and linear application systems) irrigation applications, on sandy and sandy loam soil types, for different agroclimatic conditions (A: very wet, B: average wet, C: average, D: average dry, and E: very dry).....	108
Figure 23 Simulated yield variation respect to the average (t/ha) for each combination soil*year*irrigation depending on the seasonal difference between scheduled and applied irrigation (mm).....	111

LIST OF TABLES

Table 1 Onion K_c values and crop development stages according to Allen <i>et al.</i> 1998; Piccinni <i>et al.</i> 2009; Martín de Santa Olalla <i>et al.</i> 2004; Bossie <i>et al.</i> 2009; Lopez-Urrea <i>et al.</i> 2009.....	37
Table 2 Identified key attributes, their description, and targeted audience.	43
Table 4 Model and features for the crop models reviewed. Y: Yes, N: No.	61
Table 5 Irrigation regimes for the trials in Broom's Barn in 2010, 2011 and 2012 (Source: Lacey & Ober 2011; Lacey & Ober 2012).....	63
Table 6 Drilling, harvesting and rain shelter installation dates for onions cv. Arthur in the experimental station Broom's Barn (Source: Lacey & Ober 2011; Lacey & Ober 2012).	63
Table 7 Soil moisture content at permanent wilting point (PWP), field capacity (FC), saturation (SAT) in %, and hydraulic conductivity at saturation in mm per day, for sandy loam and loamy sand soils (Allen <i>et al.</i> 1998).	65
Table 8 Average soil texture for each soil layer and irrigation treatment (LS: Loamy sand; SL: Sandy loam).	66
Table 9 Parameters (different to the default values) resulting of the calibration of AquaCrop model.	74
Table 10 Average, maximum and minimum observed yield in 2010, 2011, and 2012 in irrigation treatments A1-H3, maximum difference between treatment observations, simulated values, and difference between simulated yield and average observations.	81
Table 11 Calculated RMSE ($t DM ha^{-1}$), ME, and standard deviation of the observed data ($t DM ha^{-1}$) for each season and for the complete dataset .83	
Table 12 Modelling scenario : combination of 5 agroclimatic conditions, 2 soil types, and uniform and non-uniform irrigation.	88
Table 13 Summary of the selected weather stations and climate years used for defining each agroclimate scenario.....	93
Table 14 Characteristics of the sandy and light sandy loam soils.	93
Table 15 Reference irrigation schedule: soil moisture deficit (SMD) triggering irrigation and recommended application depth for sandy and light sandy loam	95
Table 16 Reference irrigation applications (amount and total depth) for the agroclimatic conditions 'very wet', 'average wet', 'average', 'average dry', and 'very dry' years, sandy and sandy loam soils, and the simulated onion production.	99

Table 17 Simulated maturity dates for 'very wet, 'average wet', 'average', 'average dry', and 'very dry' seasons. 101

Table 18 Summary of Kruskal-Wallis analysis. Average yield and P-value for groups considering factors soil, year, and irrigation system and their interactions. Letters indicates whether the groups are significantly different. 107

LIST OF ABBREVIATIONS

Abbreviation	Description
AWC	Available water content
CDI	controlled deficit irrigation
ACSOs	alk(en)yl cysteine sulfoxides
B	Biomass
CC	Canopy Cover
cm	Centimetre
cv	Cultivar
d	Day
DM	Dry matter
E	Evaporation
Ep	pan evaporation (mm day ⁻¹)
ET	Evapotranspiration (mm day ⁻¹)
ETa	Actual crop evapotranspiration (mm day ⁻¹)
ETc	Crop evapotranspiration under standard conditions (mm day ⁻¹)
ETo	Reference crop evapotranspiration (mm day ⁻¹)
EU	European Union
FC	Field capacity
FC	Soil Water content at Field Capacity
G	gramm
GDD	Growing day degree (°C d)
Ha	Hectare
HDC	Horticultural Development Company
HI	Harvest Index
IE	Irrigation efficiency
IWUE	Irrigation use efficiency
Kc	Crop coefficient
kPa	kiloPascal
Ky	yield response factor
LAI	Leaf area index
LI	Light Interception
ME	Model Efficiency
mL	millilitre
mm	millimetre
OM	Organic Matter
PSD	Particle Size Distribution
PSMD	Potential Soil Moisture Deficit (mm)
PWP	Permanent wilting point
PWP	Soil Water content at Permanent Wilting Point
RGR	Relative Growth Rate

RLGR	Relative Leave Growth Rate
RMSE	Root Mean Square Error
RTU	Remote Telemetry Units
SAI	Sustainable Agricultural Intensification
SAT	Saturation
SAT	Soil Water content at Saturation
SDI	Subsurface Drip Irrigation
SPAs	Special Protection Areas
SSSIs	Sites of Special Scientific Interest
SWP	Soil Water Potential
t	Tonne
TAW	total available water
Tb	base temperature
Tr	Transpiration
TSS	Total Soluble Solids
UK	United Kingdom
WP	Water Productivity (g m^{-2})
WUE	Water use efficiency
Ya	actual yield
Ym	maximum yield

Chapter 1. Introduction

This chapter highlights the importance of onions as a major food crop, both globally and nationally, identifies the key production risks and the drivers of change influencing the UK onion industry. The overall thesis aim and objectives and an outline of the thesis structure is provided.

1.1 Background

Globally, onion is the most widely produced and consumed bulb vegetable. With a global annual production of over 85 million tonnes in 2011 (FAO 2012), grown on over 4 million hectares, it ranks number 12 in global crop production (excluding cereals) (FAO 2012). Onions play an essential role in some countries; where interruption in supply can be the cause of major political instability. In 2010, for example, disastrous weather conditions caused major losses in onion production leading to a national crisis in India (Williams *et al.* 2013).

In the UK, onions represent the 4th most important vegetable crop grouping (in terms of production tonnage) after sugar beet, potato, and carrots and turnip (which are counted together) (FAO 2012). In 2011, 300,900 tonnes were harvested from 8,448 ha (FAO 2012, DEFRA 2011). Onions are available all year round in supermarkets and sold in nets, plastic bags and trays. They can also be found whole, peeled, diced or chopped in pre-cooked meals. Imports are required to fill the national production gap. In 2011, imports from EU and non-EU countries exceeded 325,000 t (valued at over £100 million) (BOPA, 2012). The greatest quantity of imports came from the Netherlands.

Onion production and crop quality are affected by local agroclimatic conditions, soils, fertilisation, pests, storage diseases, and irrigation (Kumar *et al.* 2007a; Enciso *et al.* 2009; Hanson & May 2004; Resemann *et al.* 2004; Pelter *et al.* 2004; Mohammadi *et al.* 2010). Onion production in the UK faces a number of challenges related to crop management, irrigation and pest control decision-making. The increasing demand for high quality food products and their supply year round, is adding significant pressure on farming enterprises. Additionally, national production has to cope with increasing external competition. In the

coming years, growers will have further constraints related to water abstraction licensing (Knox *et al.* 2012) and withdrawal of essential pesticides.

Agricultural land exploitation over the last few decades has affected and transformed the environment, leading to environmental policies (Habitat and Bird Directives) and designation of Special Protection Areas (SPAs). In Great Britain, some SPAs are also notified as Sites of Special Scientific Interest (SSSIs). Special regulations are applied to those areas for the conservation of the natural flora and fauna. Potentially damaging activities are restricted in those regions and their boundaries (Natural England 2012; DEFRA 2011). These environmentally protected sites are often close to areas of field vegetable production, including onions, often creating challenges for modern, intensive methods of large scale production.

Given concerns regarding food security and the need to increase production without environmental damage, the sustainable intensification of agriculture is gaining widespread interest (Pretty 1997; Fish *et al.* 2013). Native biodiversity and natural resources are now the focus of new environmental policies. Impacts on the environment could be reduced using two different but complementary approaches (Matson 1997). Firstly, recovering traditional farming knowledge including intercropping, agroforestry, and crop and livestock integration; improved fallows, integrated pest control and soil and water conservation practices (D. R. Lee *et al.* 2006). The other approach uses new technologies to allow differential application of inputs to match crop needs, known as 'precision farming'. However, there is still very limited understanding of the impacts of irrigation heterogeneity on crop production and yield within precision agriculture. With a priority of producing the highest yields from the lowest farm inputs, including irrigation, arises the necessity for studying new viable approaches for implementing precision irrigation management. This would help minimize environmental impacts and optimize productivity, thus reducing in-field variability on production.

The research presented in this thesis forms part of a broader study investigating precision irrigation in UK horticulture (Hortlink HL0196). This research deals

specifically with assessing the effects of in-field soil and irrigation heterogeneity on onion crop yield and quality.

1.2 Aim and objectives

The overall aim of this study was to assess the impacts of in-field soil and irrigation variability on onion yield and quality. With this intention, the following objectives have been identified:

1. To review and assess the scientific evidence on the relationships between onion yield, crop water use, irrigation and crop quality.
2. To parameterize, calibrate and validate a suitable bio-physical crop growth model
3. To simulate the impacts and sensitivities of soil and irrigation water variability on onion crop yield. To realise these objectives, a series of scenarios will be defined to reflect uniform and non-uniform soils and irrigation practices; their impacts on onion yield will then be simulated and statistically analysed.
4. To develop recommendations for improving irrigated onion production to minimise the agronomic impacts of in-field soil and irrigation variability on crop yield.

1.3 Thesis structure

This thesis is organized in 8 chapters:

- CHAPTER 1: Introduction
- CHAPTER 2: Water relations and irrigation requirements of onion (*Allium cepa* L.): A review of yield and quality impacts
- CHAPTER 3: Current trends and management practices in UK onion production - an industry survey
- CHAPTER 4: AquaCrop - model parameterisation for onion (*Allium cepa* L.) cv Arthur
- CHAPTER 5: AquaCrop model application – simulating impacts of irrigation heterogeneity on onion yield
- CHAPTER 6: Discussion and implications of the research
- CHAPTER 7: Conclusions
- CHAPTER 8: References

Chapter 1: The Introduction provides an overview of the study background, the rationale and nature of the problem, and the thesis aim and objectives.

Chapter 2: This chapter provides an extended literature review including a synthesis of onion agronomy, production, yield and quality response to water. It summarizes work that has been published in the science and grey literature regarding the estimation of water requirements, the effects of water stress at different development stages, and the influence of irrigation schedule on post-harvest quality.

Chapter 3 presents the methodology and results from a nationwide industry survey conducted amongst onion growers, agronomists, and key informants to understand the current state of the UK onion industry, underlying trends in management and the future challenges facing the industry.

Chapter 4 describes the methodology and results from the model parameterization, calibration and validation for the *FAO AquaCrop* model for onion production.

Chapter 5 describes the application of the AquaCrop model for the simulation of scenarios to evaluate the impacts of soil and irrigation variability on UK onion yield.

Chapter 6 summarises the key findings emerging from the research, and the implications for science and industry. Methodological limitations are highlighted.

Chapter 7 summarizes the conclusions arising from the research.

Chapter 8 presents the references cited in the thesis.

Chapter 2. Water relations and irrigation requirements of onion (*Allium cepa* L.): A review of yield and quality impacts

This chapter has been submitted to *Experimental Agriculture* (May 2013).

Summary

The results of international research on the water relations and irrigation needs of onions have been synthesized in an attempt to link fundamental studies on crop physiology to irrigation practices, and consequent impacts on crop yield, quality and storage. Following a brief introduction on its origins and centres of production, a synthesis of research on crop development including plant water relations, crop water requirements, yield response to water, irrigation systems and scheduling are presented. Most of the evidence stems from research conducted in arid and semi-arid regions notably the USA, India, Spain, and Turkey. The findings confirm that onion seasonal water requirements are highly variable depending on agroclimate, location and season, as are the crop coefficients (K_c) which range from 0.4 to 0.7 (initial stage), 0.85 to 1.05 (middle development) and 0.6 to 0.75 (final stage). Seasonal irrigation needs varied from 225 to 1040 mm to produce between 10 and 77 t ha⁻¹. The most water-deficit sensitive stages are emergence, transplanting and bulb formation. Final crop quality can also be affected by water excess as well as water deficit. Water deficit at specific stages can negatively impact on quality leading to reduced size and multi-centred bulbs. In recent years, pressure on water resources, consumer and retailer demands for quality assurance and rising production costs have meant that onion irrigation has switched from traditional low efficiency (furrow) methods to more efficient advanced (sprinkler and drip) technologies. For scheduling, soil water potential thresholds for triggering irrigation were found to be optimal between -17 kPa and -27 kPa for drip and furrow irrigation. Research is currently being conducted to maximize water use efficiency in onions, but the

deficit irrigation regimes tested under experimental trial conditions have yet to be adopted under commercial production systems.

2.1 Introduction

Global annual onion production is around 85 million fresh tonnes per annum (FAO, 2012) which is marginally less than sugar cane, the major cereals and tuber crops, soybean, some tropical and temperate fruits (watermelon and bananas), oil palm fruit and tomato. It has a very important role in the human diet as well as having medicinal and functional properties (Rodríguez Galdón *et al.*, 2008). A large number of pharmacologically important compounds have been identified in onion. They are rich in substances derived from S-alk(en)yl cysteine sulfoxides ACSOs, which are responsible for its flavour and pungency. These substances confer antimycotic, antibacterial, hypoglycemic, hypocholesterolemic, antiatherosclerotic, and antitrombotic properties to onion (*Allium cepa*) and garlic (*Allium sativum*) (Lanzotti, 2006).

In arid and semi-arid regions, onion production is entirely dependent on irrigation (Mohammadi *et al.*, 2010; Halvorson *et al.*, 2008; Al-Jamal *et al.*, 2001). In contrast, in humid and temperate areas, such as the UK and Northern Europe, supplemental irrigation is used to buffer the impacts of infrequent and/or irregular precipitation during short-term droughts (Pejic *et al.*, 2011). Here quality assurance is the major driver for irrigation and used to provide the high quality, continuous supplies of premium produce demanded by the major retailers (Knox *et al.*, 2010). Although some research has been conducted on the water relations in onion (e.g. Piccini, 2009; Pejic *et al.*, 2011; Martin de Santa Olalla *et al.*, 2004) evidence to identify the most appropriate irrigation strategy for growing onions under a range of agroclimatic and production conditions has not been synthesised in a way that could inform future industry and agronomic research needs. This chapter aims to address that gap in knowledge by integrating and systematically synthesising the international scientific literature to understand the water relations and irrigation requirements of onions to not only guide future research but also inform policies to promote best management practices, particularly as resource (soil, water, energy and labour) pressures increase. The

paper structure is similar in format to that used by Carr and Knox (2011) but draws on industry evidence based on interviews with key informants in UK onion production, including growers, agronomists and processors.

2.2 Centres of production

The genus *Allium* (*Alliaceae* family) includes onions and shallots, as well as garlic and leek. Friesen *et al.* (2006) estimated there to be c780 species of *Allium* growing across the northern hemisphere from temperate areas to boreal zones. However, they are typically found in open, sunny, dry sites in fairly arid climates (Hanelt, 1990). Their annual growth (phenology) varies widely: species adapted to summer-dry regions show summer dormancy, whilst those adapted to cold regions are winter dormant (Brewster, 2008). Onions and shallots (*Allium cepa* L.) have been cultivated for approximately 4700 years. Its primary centre of domestication is considered to be in south-western Asia, although the Mediterranean has also been considered a secondary centre due to the high variability in cultivars grown in the area (Hanelt, 1990).

Allium cepa L. includes two horticultural groups, the Common Onion group and the Aggregatum group (Hanelt, 1990). The former embraces the majority of the economically important varieties. These are characterized by the formation of large, single bulbs and usually grown from seed. Onions grown for salads and as small bulbs for pickling also belong to this group (Brewster, 2008). In contrast, bulbs from the Aggregatum group are much smaller and include varieties that form clusters, such as shallots. Another classification adopted Brewster (2008) and the FAO (2012) distinguishes fresh onion shoots and onions for dry bulb production. The latter includes brown and red, cooked and uncooked for consumption, pickling, factory-made food, dehydration, seed production, and sets (small bulbs used for next years' planting). This review focuses on this group, namely dry bulb onions. Given its international importance, there are unsurprisingly many cultivars with each adapted to the different local soil and agroclimatic conditions. An important adaptation is the day-length bulbing requirement - this is the minimum photoperiod needed to stimulate bulb development which is directly linked to location.

In order to achieve a stable year-round supply, different husbandry techniques, planting dates and varieties are grown commercially. Onions can be grown as spring or over-winter crops from seed or sets. This helps to spread the period over which harvest can occur, thus extending the period over which retailers can be supplied. The planting date also influences final bulb size. For example, onions planted in autumn are typically harvested in the following spring or early summer; those grown as spring-season onions are harvested in late summer. Using sets rather than direct seed permits earlier harvest.

Onions are a crop of global importance with centres of production ranging from the warm tropics and temperate zones to high latitudes in the northern hemisphere (Brewster, 2008). The major producers include China, India and the USA, followed by Egypt and Tunisia. Total world production increased from around 30 to 35 million tonnes in the 1980's up to 90 million tonnes by 2011 (FAOSTAT 2012).

Onions are grown across a wide variety of soils, from sands to silts, on some clays and peat. Fertility is the key determinant. The most appropriate soil pH is 6-7, although this can be lower on organic soils. However, a fine de-stoned tilth is a prerequisite for commercial drilling. These soil characteristics concur with the findings from a UK based onion industry survey in 2013. Onion is one of the most saline-sensitive crops with yields reported to decrease when E_{Ce} values rise above 1.2 mmhos cm⁻¹ (Allen *et al.*, 1998, Doorenbos and Kassam, 1979).

2.3 Crop development

Onion is typically biennial; during the first year, seeds germinate and produce leaves and bulb, in which nutrients accumulate. In the second year, the plant flowers, pollinates and produces seed. Depending on the target market, growers typically cultivate onions either as an annual (for bulb production) or biennial (for seed production) crop. Brewster (2008) identified the following stages for bulb production:

- 'Loop' stage: after germination underground, the cotyledon appears as a loop or hook above the surface;

- First leaf 'crook' or 'whip' stage: First true leaf appears, while the cotyledon is sharply bent forming a shepherd's crook or a whip;
- Cotyledon senescence: cotyledon desiccates after appearance of the second and third true leaves;
- Fourth leaf 'leek' stage: 4th leaf appears and the neck of the plant starts to thicken while first leaf withers;
- Fall of the first leaf: first leaf falls; second leaf detaches at the sheath and begins senescence from tip. Leaves five, six, and seven appear;
- Start of bulbing: the bulb begins to form; the second and third leaves desiccate; leaves 8 to 13 appear, and plants reach its maximum height;
- Bulb swelling: bulb swells rapidly and leaves 4 to 6 desiccate; leaves may bend by their own weight, and 1 or 2 more may appear. A dry outer bulb skin begins to form;
- 'Fall-down' or 'soft-neck': the neck/pseudostem becomes hollow, loses turgidity and softens, leading to foliage collapse. Meanwhile, the bulb reaches its final size;
- Bulb ripening: the outer skin dries; the foliage senesces completely and then desiccates.

The cultivated *A. cepa* varieties are characterised by slow emergence and growth rates (Brewster, 1979) compared to other field vegetables such as lettuce or cabbage. Relative vegetative growth rates have been shown to be strongly correlated to temperature. Bulb initiation occurs when the plants no longer form green leaf blades but bladeless bulb scales. The most important factors affecting bulb initiation are day length, temperature, and the ratio of red:far-red light (Lercari and Deitzer, 1987; Lancaster *et al.*, 1996). Several non-destructive methods have been used to determine the initiation of bulb formation including the bulb to neck ratio (Lancaster *et al.*, 1996), leaf ratio (leaf blade length to sheath length) and bulbing ratio (maximum bulb diameter to minimum sheath diameter) (Brewster, 2008). Dry matter partitioning varies through the different crop development stages. Prior to bulbing, most (three quarters) of the dry matter produced is partitioned to leaf blades with and only around 6% to stem bases and leaf sheaths. After approximately 90 days after emergence, all dry matter is

then partitioned into storage rather than the leaves (Tei *et al.*, 1996; de Visser, 1994).

Bulb formation is a plant survival mechanism with factors such as weed competition and water stress triggering initiation (Brewster, 1990). Weed or neighbouring onions' canopy cover absorbs light from a certain wavelength, affecting the ratio of red to far-red light; the lower this ratio, the faster the bulbing rate. This ratio decreases when light passes through the canopy, as leaves absorb the red wavelength more readily than far-red. Thus a greater leaf area index (LAI) and competing weeds accelerate bulbing maturity (Mondal *et al.*, 1986).

Several factors have been identified as determinants of yield (Brewster, 2008) including light interception (LI). The quantity of light absorbed by the leaves and then converted into harvestable dry matter does usually not exceed 80% in onions (Mondal, 1985). The final stored dry matter depends on (i) the efficiency with which the absorbed light and CO₂ are converted to sucrose by photosynthetic processes, and (ii) the proportion of photosynthetic sucrose that is transformed and stored as dry matter. Crop maturity is reached when the foliage falls over due to the weak necks. Several studies have also assessed the effects of harvesting date and fall-over percentage on storability (Boyhan *et al.*, 2004; Suojala, 2001). However, this review focuses solely on the effects of water. An excess or limit in water availability will have different consequences during each growth stage including transplant/emergence, canopy formation, bulb initiation, bulb formation, fall-over and ripening. The importance of water in each stage is briefly considered below.

Transplant/emergence

Both research and grower evidence confirms that a uniform emergence is critical in order to produce a uniform and potentially high-value crop. During this stage, some aspects are more sensitive than others to water availability (excess and/or shortage). Emergence and transplant are reported to be the most water-deficit-sensitive development stages (Doorenbos and Kassam, 1979) and crop water needs are small compared to other crop development stages. Research

established the crop coefficient K_c at early stages from 0.4 (Piccinni *et al.*, 2009) to 0.7 (Allen *et al.*, 1998). The coefficient K_c relates the reference crop evapotranspiration (ET_o) with a the crop evapotranspiration (ET_c) for certain crop, location and climatic conditions; these are explained later in this chapter. Seed water imbibition and radicle initiation, the initial stages of crop initiation, are more sensitive than radicle growth (Finch-Savage and Phelps, 1993).

Canopy formation/vegetative growth

After emergence and until the bulb initiates, the leaves emerge and grow steadily to develop a canopy. Each leaf later corresponds to a bulb scale. This stage known as the vegetative developing phase is considered to be the least sensitive to water deficit (Doorenbos and Kassam, 1979; Kadayifci *et al.*, 2005). However, water stress from the four-leaf to six-leaf stages (Shock *et al.*, 2007), and during five-leaf, seven-leaf, and three-leaf and seven-leaf (double stress) stages (Pelter *et al.*, 2004) can reduce the percentage of single centred bulbs. Shock *et al.* (2000a) demonstrated that withholding irrigation during the vegetative development phase would not affect final production as much as during the last third of the growing season, when moisture stress reduces yield. However, although it is the least sensitive stage to water stress, growers believe it is the most important. Adequate water status helps maximise canopy formation; the more leaves the plants produce at this point, the more scales the bulb will develop.

Bulb initiation

According to UK growers, bulbing is induced by a certain level of water deficit, after the crop has accumulated sufficient light and heat. Growers therefore tend to stop irrigating once the canopy has fully developed and the period for bulbing has commenced. However, no scientific evidence was found in the literature to substantiate this anecdotal industry evidence.

Bulb/yield formation

The bulb formation period is also very sensitive to water deficit, especially during rapid bulb growth (Doorenbos and Kassam, 1979). Studies by Shock *et al.* (2000a) confirm this, showing that the crop was particularly sensitive to water

deficit during the last third of the growing season. Deficit irrigation trials resulted in a yield reduction, when irrigation thresholds of soil water tensions of 50 and 70 kPa were applied during the last 3 weeks of the growing season. The soil tension at field capacity is considered to be 5, 10 or 33 kPa (Pearson *et al*, 1995). UK farmer experience suggests that a rapid maturation and very quick bulb growth can lead to reductions in post-harvest storability. In addition, large amounts of water applied during very dry conditions can lead the crop to absorb water too quickly, causing cracking and skin breakage.

Fall-over and bulb ripening

During the final crop development stage the crop dries and the outer skin layers lose moisture. Irrigation applied during this period can lead to regrowth and excess bulb moisture which then incurs extra costs for drying during storage and can increase crop wastage. Thus, it is a common practice to stop irrigation two weeks prior to harvest to avoid rots and sprouting (Kumar *et al*, 2007a).

Onion seed production

Onion plants grown for seed production are reported to be very sensitive to water stress during flowering (Doorenbos and Kassam, 1979).

Summary

- Transplant and emergence, notably during seed water imbibition and radicle initiation, are the most water-deficit-sensitive stages;
- Canopy formation is less water sensitive; however, if stressed during specific periods this can lead to multiple centred bulbs;
- It is reported that certain stress stimulates bulb initiation;
- During bulb formation the crop is very sensitive, especially during rapid growth, to both water stress (affecting yield) and excess water, which causes quick bulb expansion;
- During fall-over and bulb ripening, the crop needs to dry. Water applications at this stage can negatively impact on crop quality.

2.4 Roots

In contrast to other field vegetable crops, the scientific evidence relating to onion root development and its response to water is very limited. This could be because onion is an annual shallow-rooted crop. Onion roots are, however, widely used for structure, anatomy and physiology research purposes as they are easily available from bulbs, being thick, straight and wide, unbranched and with no root hairs. *A. cepa* develops root systems comprising of a few thick unbranched adventitious roots. These typically have a uniform width and emerge from the shoot's base (Bailey *et al.*, 2002). They only produce root hairs in moist air conditions and never in soil or solution culture (Brewster, 2008). Onions are characterized as having a shallow root system, with root penetration rarely exceeding 0.76 m (Drinkwater and Janes, 1955). However, the majority of roots are concentrated in the top 0.18 m to 0.40 m (Drinkwater and Janes, 1955; Greenwood *et al.*, 1982).

2.5 Plant water relations

Plant water transport is driven by a reduction in leaf water potential resulting from transpiration (Jarvis, 1981). Transpiration is determined by stomatal conductance and regulated by the difference in turgor pressure between guard-cells and surrounding epidermal cells. Stomata open when the turgor pressure in the guard cells is high. Water potential, CO₂ concentration, light and temperature are all known to affect the turgor pressure in the guard cells and hence stomatal aperture and closure (Ketellapper, 1963). The onion leaf epidermis is covered by a waxy layer or cuticle which contains sunken stomata (de Mason, 1990). Its guard-cells are characterised by the lack of starch and chloroplasts (Heath, 1951; Parkin, 1899). Whilst several environmental factors such as the concentration of atmospheric CO₂ and light intensity have been shown to directly influence onion stomatal aperture (Amodeo *et al.*, 1996; Millar *et al.*, 1971), due to its leaf anatomy, it is very difficult to use porometers and other stomatal conductance and water potential measuring devices. Limited evidence was thus found in the literature regarding stomatal response to water stress and correlation to onion growth. Millar *et al.* (1971) studied the stomatal response and

conductivity in plants for onion seed production and recorded an almost linear decrease in stomatal conductance with decreasing leaf water potential. The stomata closed when the leaf water potential reached between -6.5 and -7 bars (-650 and -700 kPa). Under field conditions the lowest recorded soil water potential (SWP) of -20 kPa was insufficient to make the stomata close. In an attempt to relate measured water potential and plant development, several leaf water potentials –above the stomatal closure threshold - were tested and correlated to leaf growth rate. Leaf growth rate decreased when the water potential decreased (Millar *et al.*, 1971). Moreover, a direct correlation between turgor pressure and growth rate was also observed.

Summary

- There is limited evidence on stomatal conductance due to onion leaf morphology;
- Onion stomatal guard-cells lack starch and chloroplasts;
- Stomatal conductance was linearly correlated with leaf water potential;
- Water potential at field conditions was not enough to induce stomatal closure.

2.6 Soil water measurements

Soil water content and soil water potential

Two concepts used to describe the state of water in the soil are the soil water content and the soil water potential (Kirkham, 2005).

The amount of water that is present in a soil is the soil water content. It can be quantified either based on volume or weight. The volumetric water content (θ_v) is estimated as the volume of water per unit volume of soil, and given as a percentage or units such as m^3/m^3 . The gravimetric water content (θ_g) (on a dry-weight basis) is the mass of water per unit mass of dry soil (kg/kg). The volumetric water content can be derived from the gravimetric water content multiplied by the soil's bulk density (g of dry soil/volume of soil).

Potential soil water storage is determined by the porosity of the soil. Soil total porosity is equivalent to the maximum volume of water that can be stored in a given volume of soil. Its value is determined by the size, uniformity and structure of the soil particles. A soil is saturated, when all the pores are filled with water. A typical volumetric water content for a clay soil at saturation is 50-55%, in contrast, in sand it is 35-40%.

The second expression, soil water potential, refers to the potential energy status per quantity of water in the soil compared to pure water in reference conditions. Water potential can be used to indicate directions of water movement as water will always move from an area of high potential to an area of low potential. Water in the soil is subjected to forces originating from the gravitational field of the Earth, the solid phase (the matrix potential), the action of external gas or water pressure, and any dissolved salts. These forces cause water to move within the soil, and also in plants and animals.

The resulting forces linked to the previously mentioned factors can be assigned a separated potential energy values taking a common reference point (usually free pure water at a specific height). The sum of the four potential energy values is called the “water potential of the soil” or the “total water potential”, Ψ_T . The components of Ψ_T are matric potential, Ψ_m , attributed to the attraction of the soil’s matrix; the osmotic potential, Ψ_o , caused by solutes; the pressure potential, Ψ_p , and the gravimetric potential, Ψ_g , caused the gravitational forces. Soil water potential is generally negative.

Field capacity

The concept *field capacity* (FC) resulted from the need for better irrigation scheduling to reduce water wastage and increase the application efficiency. Israelson and West (1922) studied the capacity of soils to absorb and retain irrigation water by field soils in situ, in contrast to the laboratory measurements that had been carried out before. Veihmeyer and Hendrickson (1931) defined the concept FC as “the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has

materially decreased, which usually takes place within 2 or 3 days in previous soils of uniform structure and texture”.

After a soil has been saturated, water contained in large pores will tend to drain quickly in response to gravitational forces. In smaller pores, the water remains attached to soil particles by adhesive forces.

There is substantial variation in the estimate of the soil water potential that is equivalent to field capacity. Baver et al. (1972, p.382) indicate that the matric potential associated to FC ranges between -0.0005 and -0.06 MPa depending on the soil. When it is not possible to estimate FC in the field, it is estimated as the soil water content at a soil matric potential of -0.03 MPa (Kirkham, 2005, p. 104).

Field Capacity determination

Zekri and Parsons (1999) used the following methodology to establish FC in sandy soils in Florida. The soil needs to be wetted and saturated through a long irrigation around the area where moisture measuring devices are installed, e.g. irrigating overnight. The soil profile would be saturated at the measured depths and beyond. A plastic tarpauline covering the soil would stop water from evaporating. Periodic readings of water content would provide information on the dynamic pattern of internal drainage and help determining FC. FC would correspond to the water content after downward movement of water has materially decreased (Hillel, 1980).

Permanent wilting point

If no additional water is added to the soil, it will gradually get drier as the water is taken by plants' roots and evaporates from the topsoil. The smaller the amount of water remains in the soil, the more difficult it becomes for the plants to take that water. The plants will start wilting as the soil gets drier, because the roots are unable to exert sufficient negative potential to extract the water. Permanent wilting point (PWP) refers to the soil moisture content that is held so tight to the soil matrix that roots cannot absorb it and plants wilt (Kirkham, 2005, p. 104). Veihmeyer and Hendrickson (1928) found that the PWP is a constant

characteristic of the soil, and proposed that the water content at PWP is the water content at a soil matrix potential of -1.5 MPa.

Soil water release curves

The relation between soil water content and matric potential is expressed by the *moisture characteristic* or *water retention curve*. This relation is a characteristic of each soil and helps understanding the release of water from an unsaturated soil (Fredlund and Rahardjo, 1993). It is determined by measuring the water content and the pressure potential simultaneously.

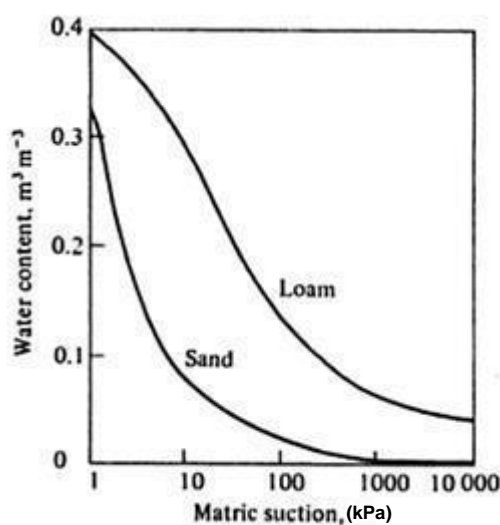


Figure 1 The relation between water content (m^3/m^3) and suction (kPa) for a sand and a loam soil (moisture characteristic curves). Marshall et al. (1976), p. 33

Figure 1 presents the retention curves of a sandy and a loamy soil. These curves are generally determined experimentally. After the soil has been saturated, it releases water stored in their pores as suction grows. It can be noted that water content at saturation on a heavier soil (smaller soil particles) is greater than on a lighter soil, where the pores are greater. This graph shows that sand releases more water under lower suction forces than do heavier soils.

Water release curves are determined in the laboratory using the following methods: Buchner funnels, pressure cells or pressure plates. The first method is

used to determine the first points of the curve, as it allows the generation of only small negative pressures. Pressure cells use positive air pressure differentials on the soil core, and pressure plate (Richards and Fireman, 1943) can produce up to -1,5 MPa.

2.7 Crop water requirements

K_c estimation

Onions have adapted to grow in a wide range of contrasting environmental, soil and agroclimatic conditions. Much of the work to estimate crop coefficients (K_c) relates to arid environments, although even here there is a wide discrepancy between the suggested values and timings for use in irrigation scheduling. To estimate crop water requirements, crop evapotranspiration (ET_{crop} or ET_c) needs to be calculated. The rate of crop evapotranspiration depends on climatic and environmental conditions, as well as the development stage of the crop. ET_c is assumed to represent crop evapotranspiration under standard conditions, defined as 'a disease-free, well-fertilized crop, grown in a large field, under optimum soil water conditions and achieving full production under the given climatic conditions' (Allen *et al.*, 1998). ET_c is estimated as the reference ET (ET_o) multiplied by a crop coefficient (K_c), see Equation 1.

$$ET_c = ET_o * K_c \quad \text{Equation 1}$$

The K_c varies throughout the season and is linked to the crop development stage – usually termed initial, development, mid-season and late season. Time is usually measured in either days or growing degree days (GDD). K_c can also be defined according to canopy cover. Several studies have estimated K_c values for onion but defined slightly different development stages for different regions. A summary of the reported values is given in Table 1. Considering the large variability in K_c estimates based on location, Al-Jamal *et al.* (1999) correlated onion K_c values to their accumulated growing degree days (GDD) and final yield. This means K_c values can be used independently of location and date. The derived K_c values were 0.43 for the initial stage (121°Cd, using 4.44°C as base temperature), up to 1.09 for 1640 heat units, then decreasing to 0.56. According

to Al-Jamal et al (1999) this approach allows growers to more readily estimate seasonal onion K_c values for scheduling irrigation.

Seasonal water requirements

Onion seasonal water requirements depend on various factors including the variety cultivated, planting density, crop husbandry techniques, expected yield, local soil and agroclimatic conditions and method/s used for irrigation application and scheduling (Jiménez *et al.*, 2010). The following studies highlight the impacts of such variability on crop water requirements. A seasonal ET_c of 390 mm (Bossie *et al.*, 2009) and 893 mm (97 l kg⁻¹ of fresh yield) (Lopez-Urrea *et al.*, 2009) were estimated using lysimeters in the Central Rift Valley (Ethiopia) and at Albacete (Spain). The latter was greater than the theoretical estimated ET_c value using the FAO methodology. Bossie *et al.* (2009) measured ET_c rates of 51, 140, 145, and 54 mm during initial growth stage (20d), crop development (30d), mid-season (30d) and late season (20d) stages, respectively. Jiménez *et al.* (2010) reviewed a number of studies on onion water requirements. For a production of between 35 and 45 t ha⁻¹, 350 to 550 mm (between 100 and 122 l kg⁻¹) were required (Doorenbos and Kassam, 1979); 1040 mm was applied using furrow irrigation to achieve a mean yield of 59 t ha⁻¹ (176 l kg⁻¹) (Ells *et al.*, 1993); 602 mm (80 l kg⁻¹) was applied through drip irrigation for a 75 t ha⁻¹ crop in Spain (Martín de Santa Olalla *et al.*, 2004) and 910 mm applied through sprinklers to obtain 77 t ha⁻¹ (118 l kg⁻¹) in Utah (USA) (Drost *et al.*, 1997). Other studies estimated a seasonal ET_c of 337 mm using micro-sprinkler irrigation in Bulgaria (Meranzova and Babrikov, 2002); 597 mm for drip irrigation in Washington State (USA); 662 mm for drip irrigated onions in Spain, and 225 to 250 mm for yields of 10 t ha⁻¹ in Eastern India (Bandyopadhyay *et al.*, 2003). Seasonal ET_c in Texas (USA) during two consecutive seasons was estimated to be between 362 and 438 mm (Piccini *et al.*, 2009). Based on these studies, the reported water requirements for onion range between 225 and 1040 mm to produce a mean yield of between 10 and 77 t ha⁻¹ (80 to 176 l kg⁻¹) across a range of different locations, under varying agroclimatic conditions and using irrigation systems with varying efficiency. The figures reported here represent 'net' irrigation needs –

additional allowances need to be made to account for system efficiency depending on irrigation method.

Any unintended water stress or soil water deficit can limit crop evapotranspiration (ET_c) and hence impact on yield. The yield response under conditions of water deficit can be estimated using the yield response factor (k_y) (Equation 2). This relates the relative evapotranspiration deficit ($1-ET_a/ET_m$) during the entire growing season or at a certain development stage to the relative decrease in yield ($1-Y_a/Y_m$), where ET_a represents actual evapotranspiration and ET_m the maximum ET (defined as $K_c * ET$). Similarly, Y_a is defined as the actual yield and Y_m the maximum yield. These parameters were combined in the following equation defined by Doorenbos and Kassam (1979):

$$k_y * 1 - \frac{ET_a}{ET_m} = 1 - \frac{Y_a}{Y_m} \quad \text{Equation 2}$$

If $k_y > 1$, then the relative yield decrease is greater than the relative evapotranspiration deficit, and vice versa. k_y values for onion have been estimated by Doorenbos and Kassam (1979) and Kadayifci *et al.* (2005). They reported values of 1.10 and 1.50 for the entire growing season, respectively. Values of 0.45 and 0.42 were estimated for the vegetative period, 0.80 and 1.02 for the period of yield formation, and 0.30 and 0.32 for the ripening stage. These show that the relative deficit in evapotranspiration during the stage of yield formation has a much greater effect on yield than the same level of relative deficit occurring during the other crop development stages. As mentioned previously, the seasonal values for ET_c and K_c are dependent on the final yield. Al-Jamal *et al.* (1999) developed a practical method to determine K_c for an expected onion yield. Two water-use functions were defined. Crop yield and seasonal water applied were related through a water production function. The evapotranspiration production function represented the relationship between yield and seasonal evapotranspiration (Al-Jamal *et al.*, 2000). These studies confirmed that there is often a direct linear correlation between evapotranspiration and yield.

Summary

- Numerous authors have estimated K_c values for onion with the following values typically being reported: 0.4 to 0.7 for the initial stage, 0.85 to 1.05 for the middle development stage and 0.6 to 0.75 for the final stage;
- K_c values measured using lysimeters differed the most in the initial and final stages;
- K_c values were correlated to GDD to minimise the effects of location and climate on ET_c calculations;
- Seasonal onion crop requirements estimated using lysimeters ranged between 390 and 893 mm, depending on location;
- Seasonal irrigation requirements ranged between 225 and 1040 mm in fields producing between 10 and 77 t ha⁻¹. The total water depths applied depend on the location, climate, irrigation application system and yield requirements for the target market;
- Onion yield response factors were estimated to be 1.1 to 1.5 (whole season), 0.42 to 0.45 (vegetative period), 0.8 to 1.02 (yield formation) and 0.3 to 0.32 (ripening).

2.8 Yield and quality response to water

Onion bulbs grown commercially need to meet stringent quality criteria. They must be intact; sound - without any signs of rotting or deterioration; clean; free and from damage due to frost; sufficiently dry for the intended use; without hollow or tough stems; practically free from pest and damage caused by pests affecting the flesh; free of abnormal external moisture, foreign smell and/or taste, and the stem must be twisted or clean cut and must not exceed 6 cm in length (except for stringed onions) (OECD 2012).

The conditions are useful in defining physical characteristics that impact on yield, but growers and the industry are generally more concerned with post-harvest quality, including skin appearance, colour, protein and total soluble solids (TSS) concentration. Different quality standards have therefore been established depending on the target market. The effects of irrigation on these parameters have been widely studied to help define optimal irrigation management practices (Martin de Santa Olalla and López, 2004; Kumar *et al.* 2007b; Lacey and Ober, 2011 and 2012; Shock *et al.*, 1998; Mohammadi *et al.*, 2010; and Enciso *et al.*, 2009). In order to satisfy year-round consumer demand, the harvested crop thus needs to be stored under conditions that will minimise any deleterious effect on quality over time, as storage inevitably triggers biochemical change (Chope *et al.*, 2006). Indeed the main factors that trigger deterioration of stored onions relate to the pre and post-harvest environmental conditions and associated biological processes (respiration, growth resumption and pathogen attacks) (Abrameto *et al.*, 2010).

Based on interviews conducted with onion growers and key informants in the UK industry, parameters such as store temperature, relative humidity and air flow are all monitored closely during storage. The bulbs' internal and external attributes are also periodically checked in commercial storehouses for evidence of rots, mould and regrowth. Sometimes, other quality indicators such as pyruvate (indicator of pungency of onion bulbs), total soluble solids (TSS), firmness, and weight decrease are also monitored closely (Chope *et al.*, 2007). For example, a recent storage monitoring study showed that both firmness and dry weight

decreased during storage (Chope *et al.*, 2007). The environmental conditions, cultivar, use of growth regulators, fertiliser and irrigation regime and harvest date, have also been studied and linked to post-harvest quality and storability (Boyhan *et al.*, 2004; Grzegorzewska, 1999; Ko *et al.*, 2002). The most important limiting factors in onion storage are fungal related – black mould *Aspergillus niger*, *fusarium basal rot Fusarium oxysporium* (Ko *et al.* 2002) - bacterial diseases - bacterial soft rot *Pseudomonas gladioli* - and sprout growth. In addition, some anatomical and physiological bulb characteristics such as scale thickness, number of dry scales, pungency, dry matter content, total soluble solids were also found to be correlated with storability (Ko *et al.*, 2002; Yutaka and Makoto, 1997).

Several studies have also investigated the response of parameters known to impact on onion quality to different irrigation regimes. For example, TSS concentration was found to be positively correlated to bulb dry weight (Chope *et al.*, 2006), with levels increased when an increasing amount of water was applied in some experiments (Kahlon *et al.*, 2011) but not in others (Pejic *et al.*, 2011). In addition, bulb protein content was found to be greatest when irrigation was 60% of cumulative pan evaporation (E_p) (compared to 80%, 100% and 120%); however, this water regime produced larger yield losses during post-harvest storage (Kumar *et al.*, 2007 b). Other experiments showed that irrigation scheduling had no effect on bulb brix or on its pungency – a measurement of pyruvic acid content (Enciso *et al.*, 2009). According to Rattin *et al.* (2011), extended wet periods enhanced the occurrence of fungi related disease. To counter this, Kumar *et al.* (2007b) suggested withholding irrigation at the end of the growing cycle. Thus it was demonstrated that moist conditions followed by 2 weeks 'drying off' prior to harvest led to better quality (Martín de Santa Olalla *et al.*, 2004; Shock *et al.*, 1998).

The effects water restrictions during crop growth on post-harvest quality and storability have also been assessed. However, the results are not consistent. For example, Rattin *et al.* (2011) reported negative impacts on post-harvest quality, as well as bulb health, whilst other studies did not show any effects on yield nor on quality (Enciso *et al.*, 2009; Martín de Santa Olalla *et al.*, 2004). Plants where

water was restricted during growth periods produced smaller sized bulbs with consequent losses in marketable quality, mainly due to sprouting or pre-sprouting softening (Rattin *et al.*, 2011). The percentage of single-centre onion bulbs, an important characteristic for the processing industry, produced under water stressed conditions was lower when stress occurred earlier in the growing season. Compared to a control treatment, the percentage of single-centre bulbs was reduced by 40%, 32% and 18% when soil-water stress was imposed at the 3- and 7-leaf, and 5-leaf stages, respectively (Pelter *et al.*, 2004).

Shock *et al.* (2000) studied the impacts of applying water via through drip irrigation at different soil water potentials (SWP). When the SWP was kept under -20 kPa, no reduction in storage decomposition was found. However, a negative impact on yield and its economic value was recorded. Kumar *et al.* (2007b) showed that a crop grown under water stress (0.6 Epan) was forced to early maturity, which resulted in the development of either immature or partially matured bulbs. These bulbs then started their rotting processes earlier. The highest yield was produced when the highest amount of water was applied (100 and 120% of cumulative Epan) using micro-sprinkler irrigation (Kumar *et al.*, 2007b).

Finally, excessive or too frequent irrigation can lead to a reduction in storability. It has been shown that increasing irrigation frequency (intervals of 10 and 15 days compared to 20 and 30 days) using surface irrigation increases storage losses (Biswas *et al.*, 2010). By increasing the frequency Biswas *et al.* (2010) found that the harvested dry matter would be reduced and storage losses increase due to rotting and sprouting. The weight loss would be greater in the most frequently irrigated plots due to higher initial moisture content. However, it was not only water that affects post-harvest quality. Other factors such as N fertilization have also been shown to trigger rotting and sprouting during storage.

Summary

- Fungal and bacterial diseases, and sprout growth constitute the most important limitations for onion storage;

- Total bulb soluble solid concentration increases with an increase in total applied water;
- The highest bulb protein concentration was found when 60% of cumulative Epan was applied. Those bulbs also experienced major losses in storage;
- Extended wet periods were linked to an increase in fungal disease;
- Generally it is recommended to withhold water applications (dry off) at least 2 weeks prior to harvest;
- Water restrictions during crop growth produce smaller bulbs and can lead to decay in storage;
- Onions grown under water stress were forced to mature early, which then produced immature or partially matured bulbs that started early rotting processes in storage.

2.9 Irrigation systems

Onion is a shallow rooting crop typically grown on light low available water holding capacity (AWC) soils, requiring frequent and small applications of water to avoid large soil water deficits accruing. An irrigation strategy with a high frequency has been shown to increase fertilizer use efficiency, reduce leaching and improve yield by increasing bulb size (Renault and Wallender, 2000). In order to compare the performance and adequacy of different irrigation systems, performance coefficients such as irrigation efficiency (IE), irrigation water use efficiency (IWUE), and water use efficiency (WUE) are often used. IE is defined as the ratio of the volume of water that is taken up by the crop to the volume of irrigation applied (Kruse *et al.*, 1987). IWUE ($\text{t ha}^{-1} \text{mm}^{-1}$) is defined as the ratio of the crop yield (t ha^{-1}) to seasonal irrigation water applied (mm) plus rainfall (Al-Jamal *et al.*, 2000). WUE is defined here as the ratio of dry matter produced per unit area (t ha^{-1}) per unit of ET (mm) (Viets, 1965; Al-Jamal *et al.*, 2001). WUE and IWUE values for onion have been estimated for different regions, under different agroclimate and irrigation conditions. The highest efficiencies resulted from those regimes in which irrigation requirements were not fully applied and seasonal rainfall was low. Under different irrigation treatments in greenhouse trials, the highest IWUE ($56 \text{ kg ha}^{-1} \text{mm}^{-1}$ for a yield of 27 t ha^{-1}) corresponded to plots receiving 75% of the water applied compared to the fully irrigated treatment

– where all the water lost was replaced. The rest of the treatments consisted of ‘no irrigation’ during specific development stages, or partial withdrawals (25%, 50%, or 75%) during the whole growing season (Kadayifci *et al.*, 2005). During a dry year in Serbia, onion IWUE was 281 kg ha⁻¹ mm⁻¹ compared to 46 kg ha⁻¹ mm⁻¹ calculated for a rainy season (Pejic *et al.*, 2011). In the semi-arid Arkansas River Valley onion IWUE for furrow and drip systems were 53.4 and 121.6 kg ha⁻¹ mm⁻¹ (Halvorson *et al.*, 2008).

Large variability can also be observed in the literature for estimates of WUE for onion. For example, values of between 89 and 102 kg ha⁻¹ mm⁻¹ were estimated from onions grown in arid conditions in India using micro-sprinklers (Kumar *et al.*, 2007); 34 to 91 kg ha⁻¹ mm⁻¹ were estimated in Serbia (producing 10 to 40 t/ha) (Pejic *et al.*, 2011) and up to 51 kg ha⁻¹ mm⁻¹ from a greenhouse trial in Turkey (Kadayifci *et al.*, 2005). Other results relating to WUE showed that irrigation should be scheduled according to seasonal climate conditions. Research by Pejic *et al.* (2011) showed that irrigation triggered at a soil water depletion of 30% gave the best and worst WUE in two different years, respectively.

Furrow irrigation

In most of the main production areas in India, the USA and Spain onions have traditionally been furrow irrigated. However, surface irrigation is often criticised for its low efficiency (Halvorson *et al.* 2008; Mohammadi *et al.* 2010; M.S. Al-Jamal *et al.* 2001). Investment in micro (drip) and sprinkler irrigation is reported to offer potential for water savings as well as increased yield and quality (size) (Halvorson *et al.*, 2008). Control of certain onion diseases is also considered to be more straightforward (Teviotdale *et al.*, 1990). However when furrow and sprinkler irrigation were compared in California’s Central Valley, no significant differences were observed either in bulb fresh weight or in the TSS (Teviotdale *et al.*, 1990). Nevertheless, due to higher soil evaporation and percolation rates, furrow irrigated crops have proven to be the less water efficient systems under similar conditions (Al-Jamal *et al.*, 2001, Halvorson *et al.*, 2008; Mohammadi *et al.*, 2010).

Overhead irrigation

Several studies have focussed on the adequacy of sprinkler irrigation, including the effects of distribution non-uniformity. For example, experiments in New Mexico by Al-Jamal *et al.* (2001) compared sprinkler, furrow and subsurface drip irrigated onions. Sprinklers were shown to be the most efficient in terms of IE and IWUE as the amount of water applied matched the amount needed to replace ET_{crop}. Subsurface drip irrigation (SDI) IE ranged from 45% to 77% due to an excessive volume of applied water. Furrow irrigation was found to be the least efficient, due to higher rates of evaporation (Al-Jamal *et al.*, 2001). Jiménez *et al.* (2010) observed that a non-uniform application can lead to undesired areas of under-irrigation in parts of a field. The consequences were lower rates of ET_a, lower yields and smaller mean bulb sizes for those plants that did not receive sufficient water. Good application uniformity is therefore a prerequisite for onion irrigation. In the UK, the most widely used system was the hose reel fitted with a raingun, followed by centre pivot and linear moves. Hose reels fitted with booms are gaining popularity, particularly as energy costs rise. Only a very small proportion of growers use drip (trickle) irrigation due to the high capital (investment) costs and supplemental nature of irrigation in a humid environment (Knox *et al.*, 2010).

Drip irrigation

Drip irrigation has been shown to be advantageous in onion production compared to furrow irrigation since the uniformity of water distribution can be very high and runoff, deep percolation, bare soil evaporation, and water interception from the canopy can all be significantly reduced, with consequent reductions in disease risk. Halvorson *et al.* (2008) studied the effects of irrigation and N on furrow and drip irrigated onions in the semi-arid Arkansas Valley, Colorado. The soil was maintained at -20 kPa. They found higher N use efficiency when the onions were drip irrigated. Yields were between 16 and 20% higher for all N treatments under drip, the proportion of larger sized onions was also higher. During two consecutive seasons, 72% and 57% less water was

applied on the drip irrigated experimental fields compared to the equivalent furrow irrigated trials. Experiments suggest that onion yield under subsurface drip irrigation (SDI) is higher than conventional sprinkler irrigation. However, the amount of deep drainage was higher under drip. Consequently the highest IE was for sprinkler irrigation (Al-Jamal *et al.*, 2001).

Summary

- A range of factors including location, soils and agroclimate, seasonal rainfall, field yield and application system influence onion WUE. Values were reported to vary between 34 and 102 kg ha⁻¹ mm⁻¹ and from 46 to 281 kg ha⁻¹ mm⁻¹ for IWUE;
- Small water deficits and dry seasons resulted in the highest IWUE and WUE. In greenhouse trials, the highest IWUE corresponded to a treatment in which 25% of the total replaced water (of a fully irrigated control) was applied;
- Traditionally most onion production has been dependent on surface (furrow) irrigation, but this method is considered to be less efficient than overhead (e.g. sprinklers) resulting in higher non-beneficial water losses, as well as encouraging disease risks. The underlying trend suggests a switch from surface to more advanced irrigation technologies including sprinklers and drip;
- Sprinklers were reported to be the most efficient method for onion irrigation, but the method is susceptible to wind drift and non-uniformity on exposed sites;
- Drip irrigation on onions is gaining popularity and has potential to deliver high uniformity and N use efficiency, when managed carefully. High levels of management (scheduling) are needed to minimise over-irrigation and deep drainage losses.

2.10 Irrigation scheduling

Irrigation scheduling is the process involved in deciding on the right time and the right amount of water a crop needs in order to maximize yield, quality and minimize water and nutrient leaching (Hanson *et al.*, 2000; Carr and Knox, 2011; Sammis *et al.*, 2012). There are many different methods available including water-balance methods, which require soil moisture monitoring, plant water potential monitoring (Sammis *et al.*, 2012) and remote sensing (Usha and Singh,

2013). The schedule can either be fixed, semi-fixed or flexible, depending on whether the irrigation intervals and depths of water to be applied need to be fixed or variable, which is a function of the irrigation application method. Several methods are commonly used to estimate onion water needs. Seasonal crop water requirements vary depending on the target market (which influences yield), and local soils and agroclimate conditions. Several studies have tried to define the most suitable approach, and evaluated the effects of different scheduling options on onion yield and quality.

Due to the shallow root system and tendency to grow onions on lighter less moisture retentive, the most common irrigation method used is overhead (sprinklers), followed by surface (furrow) and more recently micro (drip irrigation). Several authors tried to identify an appropriate irrigation threshold based on soil water potential (SWP). Early trials suggested that -27 kPa was the optimal SWP for onions under furrow irrigation (Shock *et al.*, 1998). More recently, Shock *et al.* (2000) determined the range of -10 to -17 kPa depending on the season as being an optimum schedule for drip irrigated onions in Oregon, USA. In their experiments, they maintained the SWP at a constant value by applying small, frequent amounts at -10, -20, -30, -50, and -70 kPa. Enciso *et al.* (2009) compared irrigation scheduling strategies based on soil moisture and ET for a semi-arid location in Texas. Their experiments showed that under subsurface drip irrigation the highest yields were achieved when the soil moisture was kept above -30kPa, followed by -20kPa and 100% ETc replacement. In India, the most effective scheduling for micro-sprinkler irrigation was shown to be 80% of the cumulative pan evaporation (Kumar *et al.*, 2007 b). Protein content was shown to be negatively affected by increasing the applied water depth (from 60% to 120% Ep).

Water balance models are commonly used for irrigation scheduling. Córcoles *et al.* (2013) followed Pereira and Allen (1999) methodology. It consists of generating a soil water balance taking into account daily values of precipitation, runoff, net irrigation crop ET, deep percolation, and the upward contribution from a water table, considering the rooting depth of a particular day. This balance within the rootzone allowed scheduling the irrigation of a centre-pivot-irrigated

commercial onion field in Spain. This study tried to evaluate non-destructive methods to measure canopy cover in onions using aerial digital photography. The yield achieved was 75 t ha⁻¹, with bulbs' average size of 70-90 mm (Córcoles et al., 2013).

In-situ soil moisture measurement

As expected, there is no scientific evidence on the appropriateness of specific soil water measurement devices for onion irrigation scheduling. The most frequently used devices to monitor soil moisture content and potential include capacitance probes, neutron probes and tensiometers. Consultancies usually install and maintain the probes in farmers' fields with technical staff then responsible for taking readings and informing the farmer. Due to their cost growers often limit the number of probes to a few fields and then extrapolate the relative trends in soil moisture to other fields with similar soils across the farm.

Simulation models

In contrast to other crops, there has been limited development and validation of biophysical crop growth models specifically for onion. Two models including ALCEPAS (De Visser, 1994) which simulates crop growth and yield under non-restrictive conditions or limiting water supply and MOPECO (Alvarez *et al.*, 2004) which combines crop water needs and yield with an economic assessment have been produced, but their application has been limited to Spain.

Irrigation scheduling services

In commercial production, irrigation is scheduled using a combination of soil moisture measurement, water balance models and crop observation. Most growers still rely on subjective visual observation and soil augering rather than objective scientific tools. Growers without access to automatic weather station data typically estimate evapotranspiration from soil moisture readings and use external irrigation management services or agronomy consultancies.

Deficit irrigation

Irrigation efficiency can be increased under irrigating crops in such a way that yield is not affected. Deficit irrigation has the potential to reduce irrigation costs

and increase both IE and IWUE (English and Raja, 1996; English, 1990; Al-Jamal *et al.*, 2001). This leads to the need of identifying the crop stage at which this deficit could be applied without affecting onion yield or its quality. Martín de Santa Olalla *et al.* (2004) aimed to find at which phenological stage, Controlled Deficit Irrigation CDI could be applied. Interesting results came out of this work, as dry matter yield was not affected by the total volume of water intake. However, in their experiments significant effects were observed on yield, when water shortage was applied during bulbification and ripening. Moreover, water restrictions at development and bulbification stages increased the weight percentage of small bulbs (<60 mm). Additionally, weight percentage of premium (75-90 mm) sized bulbs increased with increasing water doses during growth and ripening (Martín de Santa Olalla *et al.*, 2004). Other studies showed yield reduction (-26%) after withholding irrigation at 3- and 7-leaf stages (Pelter *et al.*, 2004). Water deprivation during the growing cycle delayed bulbing initiation, reduced total dry weight, produced smaller bulbs, and developed earlier sprouting in storage (Rattin *et al.*, 2011).

Irrigation scheduling constraints

Most studies in the literature regarding crop response to water relate to arid or semi-arid conditions where water scarcity is an issue. Onion response to deficit irrigation has been widely studied to assess when and how much the crop can tolerate water stress without reducing yield or quality. These techniques have been tested under experimental trials (e.g. Rattin *et al.*, 2011; Martín de Santa Olalla *et al.*, 2004; Ayas and Demirtas, 2009), but no evidence on its commercial application is reported in the literature. In humid or temperate regions such as the UK, where rainfall is highly variable and unpredictable, one of the major concerns highlighted by growers is excess rainfall late in the growing season. This can create major problems for harvesting, reducing the value of production and raise post-harvest drying costs. Scheduling irrigation under supplemental conditions is difficult in terms of timing the amount and frequency of irrigation so as to maximise the use of effective rainfall and limit the risks associated with nitrate leaching and reducing water efficiency due to over-irrigation. Most UK onion growers and agronomist consultants reported using capacitance probes or

neutron probes for scheduling advice; they aim to apply 15-20 mm at a 15-20 mm soil water deficit during canopy development and then 15-25 mm during bulb formation. However, these guidelines are always validated against visual observation of the crop status. SMD measurement equipment requires adequate calibration and maintenance for the measurements to be interpreted correctly. It has to be taken into account, that probes generate punctual readings; therefore, its position in the field is of extreme importance to produce representative SMD values.

Summary

- -17 kPa was determined as the optimal drip irrigation threshold;
- For SDI onions, soil moisture content kept above -30 kPa gave the highest yields;
- -27 kPa was determined as the optimal furrow irrigation threshold;
- The most appropriate schedule for micro-sprinkler systems was to apply 80% Epan;
- The most popular scheduling methods used are water balance methods and soil water potential and soil water content measurements, including capacitance probes, neutron probes and tensiometers;
- Growers always complement objective scheduling with visual crop observation;
- Deficit irrigation has been tested on experimental trials, but no evidence was found about commercial uptake;
- CDI during the bulbification and ripening periods reduced yield significantly; and during development and bulbification produced smaller bulbs.

2.11 Drivers for change

Onions are grown in a wide variety of agroclimate conditions, with irrigation being an essential component of production to maximise yield particularly in arid and semi-arid regions. In contrast, in humid or temperate regions, supplemental irrigation is widely used but principally for quality assurance, as the benefits of irrigation can be significant in delivering high quality continuous supplies of produce demanded by the major retailers and processors (Knox *et al.*, 2010). But

rising energy costs for irrigation coupled with increasing consumer demands for traceability and environmental sustainability are also exerting new pressures on current approaches to onion production. In arid regions such as Spain, Turkey, and parts of the USA, where onion production is well established, the current focus is on water saving to reduce non-beneficial losses (Hess and Knox, 2013) and improve WUE. Traditional gravity-fed furrow irrigation schemes are gradually being replaced by modern overhead (centre pivot) and micro (drip) systems. However, in Spain an energy trade-off is underway between improving WUE and managing the costs associated with irrigation modernization. Here the original conveyance (open channel) systems that supplied water under gravity have been replaced by pressurized (piped) systems. Whilst national water use has doubled, individual water use efficiency increased by 21% between 1950 and 2007, and energy consumption increased by +657% (Corominas, 2010). Thus, energy is becoming the major driver of change in production rather than water resource availability. Any improvements in water efficiency are therefore closely linked to significant increases in dependence on energy with consequent negative impacts on emissions and the carbon footprint of the irrigated agriculture (Rodriguez-Diaz, 2012). Climate change threatens to exacerbate the situation; coupled with increasing water scarcity and greater demands for environmental regulation, advanced irrigation and precision irrigation (Monaghan *et al.*, 2013) will inevitably play an increasing role in global irrigated onion production.

2.12 Conclusions

This review of onion productivity and water use relations has highlighted a number of salient issues. Onion is particularly sensitive to water deficits during emergence and transplant, and to both deficit and water excess during the rapid bulb growth periods. Water restrictions during crop growth (total water withholding and controlled deficit irrigation) resulted in lower yields and smaller bulbs. Early bulb maturity was identified as a result of growing the crop under water stress, causing secondary problems including early rotting in storage. Several studies have determined onion K_c values and reported on contrasting values (0.4-0.7 / 0.85-1.05 / 0.6-0.75) depending on climate and location. An attempt to minimize these differences was reported by correlating K_c to GDD.

Total irrigation requirements are reported to range between 225 and 1040 mm to yield between 10 and 77 t ha⁻¹, leading to WUE and IWUE of 34 to 102 and 46 to 281 kg ha⁻¹ mm⁻¹, respectively. Irrigation and water efficiency is thus highly influenced by agroclimate, the method of irrigation application and final yield.

Quality is a key constituent of modern onion production. The most important limiting factors in storage are sprout growth and bacterial and fungal diseases, with the latter being strongly correlated to prolonged wet periods. Current trends show a move away from traditional surface (furrow) irrigation to more advanced and efficient micro (drip) and overhead (sprinkler) systems capable of applying water with greater precision and timing. Drip application is still a minor use, but research shows it can achieve the highest nitrogen efficiency use, reduce water losses and improve crop quality (by avoiding soil splash and high humidity conditions in the canopy). Finally, the drivers of change including the need for greater product traceability, quality assurance and managing the spiralling costs of energy in irrigated agriculture seem to be the dominant drivers of change within the onion industry. Future research should focus on these aspects and encourage better integration of our detailed biophysical understanding of onion crop agronomy with new developments in soil and water management.

Table 1 Onion K_c values and crop development stages according to Allen *et al.* 1998; Piccinni *et al.* 2009; Martín de Santa Olalla *et al.* 2004; Bossie *et al.* 2009; Lopez-Urrea *et al.* 2009.

Author	Year	Developing stages (days after planting)						Total crop length	Country Region	
		K_c								
Allen <i>et al.</i>	1998	Initial	Development	Mid-season		Late season		150	Mediterranean	
		15	40	110		150				
		20	55	165		210		210	Arid Region	
		0.7	0.7-1.05	1.05		1.05-0.75				
Piccinni <i>et al.</i>	2010	Emergence	2 leaves	2 to 4 leaves	5 to 6 leaves, beginning of bulbing	7 to 9 leave, bulb development	Bulb fully developed	Dry leaf stage	190	Texas, USA
		25	75	105	130	152	175	190		
		0.4	0.55	0.75	0.85	0.9	0.85	0.7		
Martin de Santa Olalla <i>et al.</i>	2004	Settling	Development	Bulbification		Ripening		150	Spain	
		52	77	135		150				
		0.5	1	1		0.7				
Bossie <i>et al.</i>	2009	initial	Development	Mid-season	Late season				100	Ethiopia
		20	50	80	100					
		0.47	0.47-0.99	0.99	0.99-0.46					
Lopez-Urrea <i>et al.</i>	2009	Establishment	Development			Bulb growth	Ripening		168	Spain
		52	114			144	168			
		0.7	0.7			1.05	1.05-0.75			

Chapter 3. Current trends and management practices in UK onion production - an industry survey

3.1 Introduction

This chapter describes an industry survey to gather new evidence and data on the current state of the UK onion industry, including information on typical onion farming characteristics, crop and irrigation management practices and future challenges facing the industry.

The aim of this chapter was to provide supplementary industry information to complement scientific evidence presented in Chapter 2 (Objective 1), to obtain data to undertake the crop model calibration and validation, and to help define the scenarios needed to simulate the impacts of soil and water variability on onion yield (Objectives 2 and 3). The main onion production areas were first identified, and then key informants targeted and interviewed. This chapter presents the survey methodology and main findings.

3.2 Methodology

The methodology consisted of five defined stages:

1. To identify key onion growing areas in order to target the industry survey
2. To identify key attributes of importance in onion production
3. To draft a questionnaire and check with growers
4. To conduct interviews with farmers and industry representatives in the identified areas
5. To produce a database of relevant information and a summary narrative on the key findings

3.2.1 Identifying target areas for survey

Onion production has a very important role in UK agriculture. However, there are no official published figures regarding its regional (county-scale) distribution. DEFRA statistics (<https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom>) do not include onion production by region, but have produced detailed data on vegetable crop production. EDINA

<http://agcensus.edina.ac.uk/demo/index.html>) provides DEFRA agriculture cropping census data which can then be used to generate land use maps for particular crop categories.

Figure 2 shows the distribution of field vegetable crop production across England and Wales (data for 2010, grids of 2km by 2km). This group of crops includes lettuce, tomatoes, carrots, mushrooms, onions, cabbage, calabrese and cauliflower (DEFRA 2010). A higher density of production is found in the South West and South East areas of Wales, across the West Midlands and Lancashire; other production regions are concentrated in the East of England, mainly the centre of East Anglia and Humberside.

In order to identify the main onion cropped areas, other factors also needed to be considered. Onions are typically grown on well drained fertile land on open, sunny, dry sites in fairly arid climates (J. L. Brewster 2008). Figure 3 and Figure 4 helped identifying potential onion growing areas based on soil properties and average climatic conditions. Figure 3 presents a classification of England and Wales soils based on their texture. Figure 4 presents UK agroclimatic spatial variability given by the average (from 1961- 90) estimated $PSMD_{max}$.

By combining the information presented in each of these three figures, areas where soils, agroclimate and known to have a high concentration of vegetable cropping were assumed to be suitable for onion production. These areas were East Anglia and Essex, southern areas of Lincolnshire, and the northern regions of South East of England.

Figure 2 Regional production of outdoor field vegetables based on EDINA and DEFRA (2010) in the England and Wales in 2010

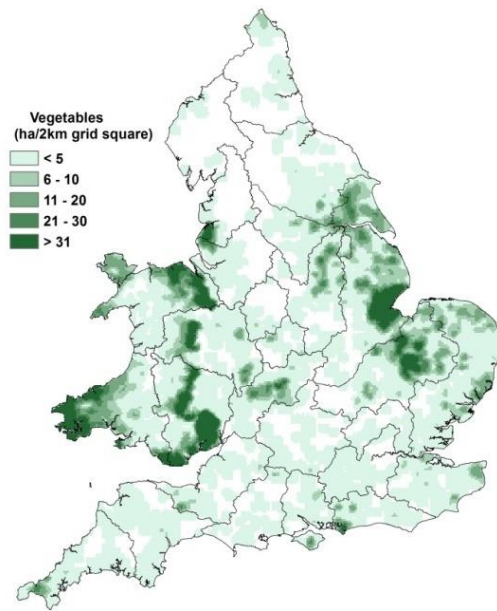


Figure 3 Classification of England and Wales soils by their texture (Source: National Soil Research Institute)

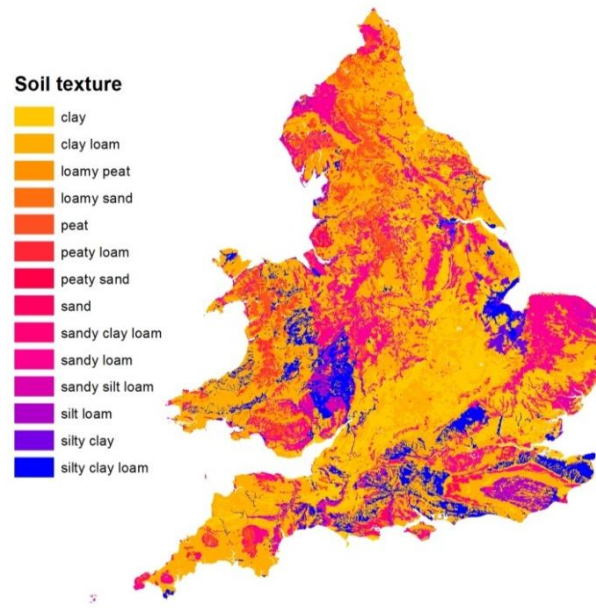
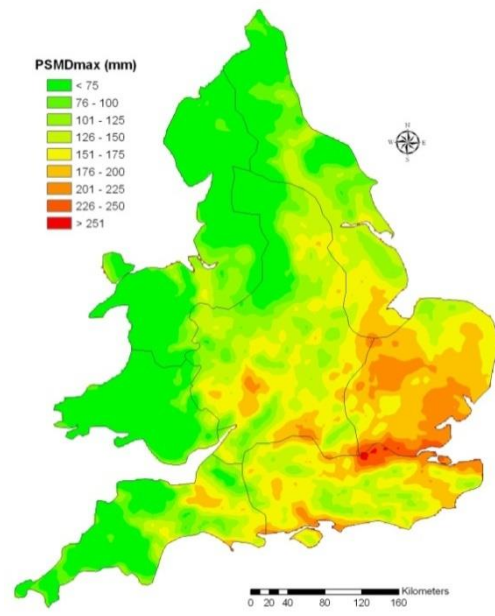


Figure 4 Spatial variability in agroclimate (PSMD_{max}) for the UKCP09 long-term average baseline (1961-90) in England and Wales



In any fresh produce supply chain the main elements always include producers, processors, retailers and finally the consumer. This study focusses on crop response; therefore it looks at the production side with attention to processors' contribution in terms of marketability and quality issues. Bearing this in mind the targeted volunteer key informants are growers, agronomists, and members of the onion packing industry.

3.2.2 Identifying the key attributes of onion production

In order to complete Objectives 2 and 3, a range of information was essential. First, the types of evidence and the potential key informants needed to be identified. Detailed information regarding onion production in the UK was also required to support the scientific evidence found in the literature. This included information relating to the crop (grown varieties, growth cycle stages and length, potential yield, plant response to water) and soil (preferred soil characteristics, crop response to certain soil properties), as well as management practices (planting date and planting density, irrigation schedule, and fertilisation).

Growers would share their knowledge on crop performance and general management aspects. Their contribution would be based on their experience on their farms, with their particular conditions of soils and climate. Growers would share daily challenges and concerns about the future.

Usually agronomists provide advice to a wide range of growers and across a large geographical area. Agronomists could contribute to creating a wider overview of UK onion farming thanks to their experience and technical approach. They could also contribute information on how the market for onions functions, crop management, and plant interactions with environmental factors.

The industry informants (cooperative managers and informants at the packing industry) could provide information on storability, packing and the marketable end of the production chain.

A summary of the key sectors targeted for interview and the types of survey respondent are summarised in Table 2.

Table 2 Identified key attributes, their description, and targeted audience.

Key attribute	Description	Targeted audience
Farm characteristics	Location, total area, area dedicated to onions	Growers, agronomist
Onion production	Targeted market and prospects Varieties and specific requirements	Growers, agronomist, packing industry
Crop management	Growing cycles, planting practices, plant density, planting conditions, harvest time	Growers, agronomist
Soils	Most desirable soil characteristics, soil tillage, effects on crop production	Growers, agronomist
Irrigation and fertilisation	Irrigation practices, equipment, scheduling and effects on yield and quality Fertilisation practices	Growers, agronomist
Yield, post-harvest quality	Average production, variability, bulb size distribution quality aspects and factors affecting storability Commercial specification and quality thresholds Storage, packing and processing industries	Growers, agronomist, packing industry

Due to these differences, three questionnaires were developed. The grower and agronomist questionnaires had to explore general crop production management (e.g. varieties, soils, fertilisation, irrigation), growers' concerns and production targets. The industry questionnaire had to be related more to crop quality, marketability and storage aspects.

3.2.3 Produce questionnaire

Questions had to be clear and concise. If possible, include yes/no questions and multiple choice answers. The final questionnaire was the results of an iterative process involving very helpful and experienced onion growers and agronomists. They were planned for one hour meetings (Appendix A).

3.2.4 Conducting the interviews

After the main UK onion growing areas were identified, informants within each area had to be found and engaged with the project. Finding growers, agronomist and industry members volunteering to collaborate was the initial step. A list of potential interested growers and industry members was put together using the

British Onion Producers Association (BOPA) members' list, existing contacts, and clients of Vegetable Consultancy Services (VCS).

In order to involve the targeted audience with the purpose of the survey an explanatory e-mail was addressed to all potential survey interviewees. This explained the intention of assessing the viability of precision irrigation in UK onion production and asked for their collaboration in a one hour meeting. Meetings were arranged with the interested parties. During January and February 2013, farms, cooperatives, packing industries and agronomists were visited and the interviews completed. The names, location, and farm details for the growers involved, as well as the details for the industry representatives and agronomists were kept confidential.

3.2.5 Survey outputs

Once the interviews were conducted, the information was compiled and analysed. The outcome was a narrative including all the findings, and the contribution of each components of onion production. These results would be used in the parameterisation of a crop growth model and in the generation of scenarios, as well as to contrast the results produced by the model.

3.3 Results

This section presents the summary findings from the industry survey. It is organized into three sections (i) general crop and soil management, (ii) irrigation and fertilization practices, and (iii) yield and quality issues.

3.3.1 Crop and soil management

Most onion production areas were identified by the interviewed agronomist as in East and West Anglia and the South East. Onions in the UK are usually part of a 6 to 8 crop year rotation cycle. Cereals (wheat and barley) alternate with root crops (potatoes, sugar beet and onions). Average field size is of around 10 ha according to the growers and agronomists interviewed. Minimum field sizes are 5 ha and maximum 25 ha. Around 400,000 t are annually harvested from 10,000 ha in the UK with an average production of 40 t ha⁻¹ (DEFRA 2010).

Two onion groups can be distinguished: red and brown. Brown onions are the most widely grown (approx. 80% of annual UK tonnage (BOPA 2013)); hence market demands roughly one quarter red onions, and three quarters brown bulbs.

The agronomists reported that most commonly drilled brown varieties are Centro, Arthur, and Vision, followed by Armstrong, Bennito, Hybelle, Hybing, and Hytech. Also very important, but with less drilled area are Hybound, Napoleon, and Tangito. Sturon and Jagro are the main brown varieties grown from sets. In organic production: Hylander and Santero are the growers' favourites. The growers and agronomists agreed that Red Baron is the most commonly drilled red onion; followed by Redspark, Red Tide and Renato. Most popular red sets are Electric, Red Emperor, and Reddawn.

In the growers' experience, red onions are more difficult to grow, whilst agronomists stated that in general, red varieties are more susceptible to foliar diseases, have germination problems, are less productive and are more prone to storage problems. Nevertheless, the market value is higher than for brown

onions, hence about half of the growers interviewed agreed that the potential benefit of growing red onions outweigh the risk of lower production.

Generally, in onion trading there is no variety-specific demand, in contrast to other crops such as potatoes or lettuces. Despite this, a characteristic such as storability is still a key factor. The storing properties of onion bulbs will determine the time when onions are sold. The time when the onions are sold determines the price of the onions influencing growers' perceived price. A growers' storage capacity and targeted marketing time, would determine whether short or longer storing varieties would be chosen. Onion breeders have developed varieties which are adapted to different growing conditions and suit growers differently. In recent years, the varieties have changed and improved their characteristics, especially storability.

Agronomists also recommend specific varieties based on site suitability. They focus on soil properties, weather conditions and the growers' experience with those varieties in the past. Storability is also a decisive factor in the final selection of variety. Considering growers' storage capacity and target marketing time, short or longer storing varieties would be recommended and chosen. Productivity, potential to produce high yield, drought tolerance or a more developed root system are other factors considered when choosing or recommending varieties.

Like many other vegetables, onions can be grown either from seed or sets, over winter or in spring. In the UK, drilling in March to harvest at the end of August or beginning of September is the most common practice. Nevertheless, an early production (July to beginning of August) can be harvested from spring-planted sets. The growers interviewed drilled brown onions in spring 2012 and some planted a smaller area (10-40%) with sets. Half of the interviewees also produced red onions, either from sets, seeds or a combination of both.

Sets have the advantage of producing an earlier crop, filling an early niche in the market before bulbs from seeds are available, allowing producers to receive a premium price for them. Generally, sets produce a reliable and consistent

yield; this is of special importance for growers during bad seasons. Sets also allow the use of heavier soils, not suitable for seeds. Some growers' experience with sets was positive in terms of required inputs. They reported that fertilizers, agrochemicals, and irrigation were lower than for crops grown from seeds. Another advantage of sets is that they allow an even distribution of the harvest, spreading the workload evenly during summer.

However, growers reported that the big disadvantage of sets is the high cost. Set planting costs are over three times higher than seeds. Additionally, the resulting onions are coarser, have thicker necks and are less uniform than onions grown from seeds. In addition, since they are more prone to bacterial diseases, storability is not as good as onions grown from seed. Consequently, many growers, especially those with smaller farms, prefer growing onions from seeds so as to avoid further expenses.

All the crops harvested in 2012 by the growers were spring-grown crops, except on one of the farms where a small percentage (5%) was produced over winter. Sets of short-day onions, planted in winter, can be harvested very early, generating a high value crop; however this practice entails a higher risk. Usually, the bulbs produced are only suitable for short term storage and the yields are slightly lower than for a spring-grown crop.

The target for an onion grower is to have a final plant density of c.50-55 plants m^{-2} of brown onions (or a distance of 75 mm between bulbs) and 42-55 plants m^{-2} of red onions. To reach this target density, an initial planting density of 55-65 seeds m^{-2} is drilled with traditional drilling, or 22.5 seeds m^{-2} with precision drillers or 45-55 sets would be planted. Onions typically grow on ridges with 4 to 6 rows of placed seeds, or 4 double rows of precisely drilled plants. Beds are formed with centres being 1.83m apart (Figure 5).

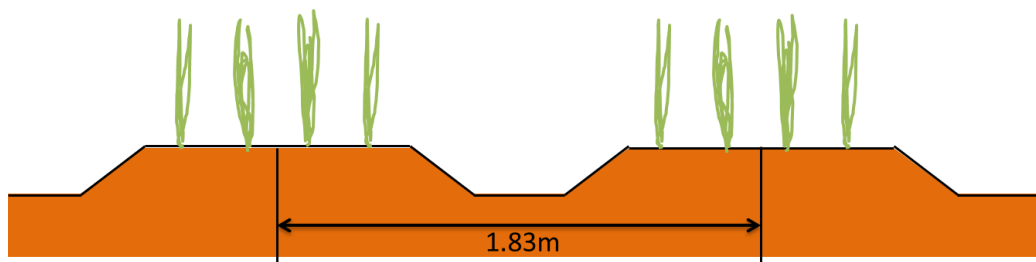


Figure 5 Typical onion planting layout: bed centres 1.83 m apart with 4 rows of plants

Usually growers plant brown sets from mid-January and red from the beginning of March onwards. Seeds are drilled in mid-March. However, when conditions are favourable, growers prefer to drill from the middle to end of February.

The essential requirements for good germination are a fine soil tilth, soil temperature (over 5°C), “appropriate soil moisture content” (close to FC in the surface, with enough water stored in immediate soil layers), and favourable weather conditions. Soils need to have some moisture so that seeds can emerge. However they need to be dry enough to allow the machinery to work. The temperatures need to be rising and no rain should fall immediately after drilling, as crusts could be formed on the soil surface.

General crop development stages and the corresponding time for the UK are shown in Figure 6.

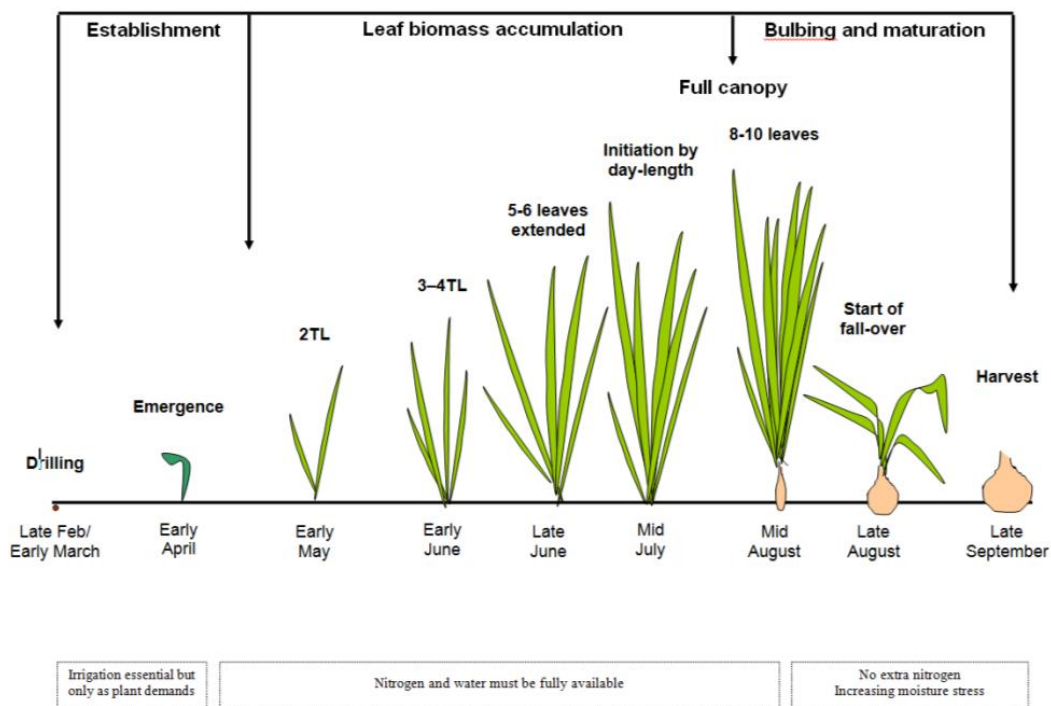


Figure 6 Typical development stages for an onion crop in the UK (pers comm, 2013)

Onions are ready to be harvested from mid-July (for sets) to end of August-September (for seed). The duration of the crop in the field ranges from 150-180 days and 180-200 days for sets and seeds, respectively. Growers tend to start harvesting at 50-75% fall-over. According to all those involved in this survey the ideal harvest time would be at 100% fall-over; however, weather conditions affect harvest and quality aspects. Onions have to be harvested before the soil and the mature crop get too wet.

Onions are grown on a variety of soils ranging from light sands to clay-loams, organic sands, and alluvial soils. In East Anglia onions are grown on sandy loam to sandy soils; clay loams in Bedfordshire, and gravelly-loams in Essex. These soils are frequently over chalk or show some chalky areas on their surface. Sand and sandy-loams were identified by growers and agronomist as the best soils, showing highest yields and better quality under irrigated conditions. Nevertheless, silty soils were recognized for better yields during dry years since they have better water retention capacity.

Organic soils and silts have the potential for very high yields in good years due to nutrient availability, however in wet conditions harvesting can become very difficult. Heavier soils –clay loams and gravelly loams – give lower quality yields in wetter years, because of the poor drainage.

Most of the interviewees agreed that the varieties they grow have different requirements in terms of soil, and some of light requirements. Generally red varieties and hybrids develop poorer root systems, which make their cropping more difficult. Lighter soils would allow growers to plant brown and red sets earlier in the season, hence less vigorous varieties, such as Centro, would be planted on these soils, and some producers believed that Red Baron should be grown on these soils. On the other hand, whilst heavy soils are generally avoided for onion production, Centro would also perform well on these. Red varieties in general are grown on warmer more fertile soils.

A very common varietal classification distinguishes early from late varieties. This refers to the time when maturity is reached. Accordingly, growers choose early varieties- more vigorous, with quicker growth, such as Vision- for 'slow' soils. 'Slow' soils refer to those that take longer to heat when the air temperature increases in spring. These are usually chalky soils.

Very frequently, chalky soil patches are present in UK fields. These soils have a slower response to air temperature rise. Agronomist and growers observed that onions grown on these areas develop slower than on soils with lower CaCO_3 content and darker colour. These differences in the developing speed affect uniformity and time of maturity.

Based on soil properties, agronomists would suggest growing thick skin varieties on organic soils, and medium skin varieties on sands. Onions grown on those soils tend to form thin and thick skins, respectively. On silty soils, too vigorous varieties may grow too quick and could explode; therefore, in this case less vigorous varieties would be suggested.

3.3.2 Irrigation and fertiliser management

Watering either 'too much' or 'too little', and its timing can have direct effects on yield and its quality. A certain level of water stress is required for bulb initiation. In case of bulbing failure no proper bulbs will be formed. Additionally, the crop needs enough water during bulb formation or bulbs will be of a smaller size and yield will then be constrained. Furthermore, during the final stages of onion development too much water could be detrimental. If the crop remains too wet and green, it will continue growing and maturity will not be reached. Accordingly, late irrigation or rainfall could affect size distribution and in store quality. Therefore, irrigation needs to stop previous to harvest.



Figure 7 Irrigation by linear move on a red onion cv *Red Baron* field on a commercial farm, Elveden Estate (Norfolk), August 2012.

Irrigation is a pre-requisite for onion production in the UK. All the growers interviewed were able to irrigate all their onion fields. Some growers' cooperatives and supermarkets would not accept producers who are not able to irrigate their onion fields. According to this survey, the most common water application methods used by onion growers are hose-reel fitted with booms or linear moves, rain guns and centre pivots. Boom and linear moves are the most widely used systems. Most farms would either use only booms, or use in approximately the same proportion booms and linear moves. Rain guns fitted to a hose reel are normally used for difficult access areas. Only one of the growers used exclusively rainguns.

Irrigation is used to assist at crop establishment and reduce water deficit during later stages. Growers believe irrigation helps to improve quality, ensuring the crop grows evenly in terms of development stage and consequently size. Although not very frequent, irrigation is also used to complement the application of certain herbicides or fertilisers in very dry periods. Occasionally, fields are irrigated to improve soil stability, prevent wind erosion, and remove soil capping formed after drilling. Unlike other crops, irrigation is never used to improve harvest, usually onion bulbs and machines need dry soils at harvest.

All the interviewees scheduled irrigation and had soil moisture monitoring equipment. These are either owned by the growers or by external companies. Measurements of soil moisture allow crop evapotranspiration and water balances to be calculated. A small proportion (3 out of 9) of growers rely completely on external consultants to determine irrigation time. Most of them take the advice as a suggestion, and decide the most adequate time to irrigate after walking the crops, digging the soil and looking into the crop appearance. Usually it is on larger farms, where they decide irrigation themselves, whereas smaller growers tend to rely entirely or partially on external advice.

Soil moisture reading equipment is installed in 20% to 100% of the onion crops, depending on the farm size. Bigger estates tend to have probes in a few fields which they believe are representative of the rest. In case of having different soils or conditions, they would monitor 1 in every 3 or 5 fields of similar characteristics. However, all the crops would be regularly walked and/or dug individually.

Onions have different water requirements according to their developmental stage. Development of a good canopy early is crucial to ensure good production; therefore, irrigation is crucial at this stage, right after emergence or after 2 or 5 leaves have formed. In this case, small amounts of water would be applied, as water is only needed in the top centimetres. During canopy development 15-20 mm are applied at 15-20 mm deficit. Growers and agronomist stated that bulbing is induced by a certain level of water deficit.

Therefore growers withdraw application when the canopy has fully developed and the time for bulb formation has arrived. After bulbs are formed, the trigger for irrigation is of 15–25 mm. Irrigation needs to be stopped according to the growers 2-3 weeks before harvest.

3.3.3 Yield and quality

Marketable production

After being harvested, bulbs are cured, dried and stored. Storing facilities can be on-farm or off-farm, the latter belonging to cooperatives or packing companies. Onion storability is a very important characteristic, as it is a determinant factor for national market self-supply. Domestic production supplies onions from the end of July-August through to April-May. Consequently, there is a period of time, during which international trading is needed to feed the lack of local supply. The market demand is then fulfilled by imports from the Southern Hemisphere (e.g. Brazil, New Zealand, South Africa), the Netherlands, Egypt, Poland or Spain (BOPA 2013). Bulbs produced nationally which are stored for long periods before getting into the market generate high storage costs.

Onion production is distributed to the final consumer through supermarkets, household markets, or processing industries (e.g. ready-to-eat meals). If the quality is not high enough, the crop will be sold as animal feed for which the quality requirements are less demanding, as is the growers' income. According to the agronomists interviewed, 55% of the production is sold to supermarkets, 30% gets to final consumers through household markets and 15% goes into the processing industry.

Most of the growers aim to produce bulbs of 60-80 mm diameter. Rarely, growers prefer smaller bulbs (50-70 mm) or slightly bigger (65-80 mm). Figure 8 shows the average targeted size distribution and the average of the size distribution reported by the growers. Most growers aim (realistically) at getting 70-90% of the premium 60-80mm bulbs and split the rest into the bigger (>80mm) and smaller (40-60 mm) fractions. Of the total green yield, the

smallest bulbs account for 5-50%, bulbs of 60-80 mm make up 60-70%, and the biggest division (over 80 mm) 0-25%.

When growers were asked to choose between a high yield and a specific size, the answers were split equally; however, growers would always prefer the most profitable option. Farmers who are satisfied with their harvested bulb sizes would choose to produce higher yield.

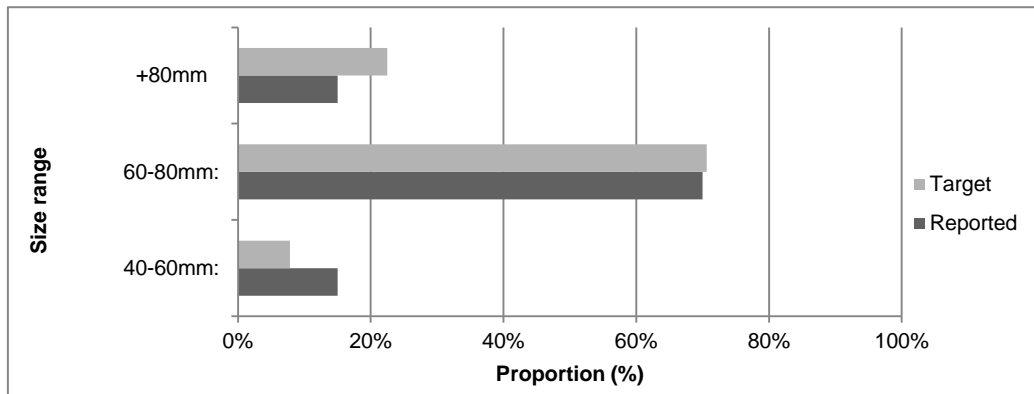


Figure 8 Growers' reported and targeted onion size range (mm) and proportion (%).

Size distribution, which is a key factor determining crop value, depends on uniformity during the early crop stages, particularly at establishment. Therefore, any issues arising at germination, emergence, and establishment would have a direct effect on crop value.

Yield: average production and variability

According to the growers and agronomist interviewed the average brown onion green yield ranges from 45-55 t ha⁻¹ for sets and 50-60 t ha⁻¹ for seed grown onions. Red onions are slightly less productive, yielding 40-50 t ha⁻¹ for both, bulbs produced from seeds and from sets. Nevertheless, in some years with very good conditions (warm seasons and irrigation applications), maximum green yield of 70-80 t ha⁻¹ in browns and 60-70 t ha⁻¹ in reds were reached.

Yield is very variable. The producers pointed out that yield can vary from year to year, from field to field, and even across a single field. Their experience showed

that during different seasons (depending on weather and light/cloud coverage conditions) onion production can vary between 30-50% relative to annual maximum yield. They estimated the variability between fields during the same growing season in 15-30%. These approximate data have been contrasted to yield records of a particular grower (see section A.4 in Appendix A). However, in years like 2012, when weather conditions were not optimal, some fields could produce a crop that was only one third of other fields. In 'bad years', variation in yield resulting from differences in soil type were exacerbated.

In-field variability has not been measured by any of the growers. However, most growers think it could be as large as between fields. Additionally, many of the interviewees identified 'bold' areas in their fields which contrast to areas with a normal plant density. Yield differences between those could be up to 100%. Looking into individual fields, the differences were greater for unfavourable weather conditions.

Water and soil effects on yield

Growers identified 'too much and too little' as the main water related issues affecting yield, in addition to its timing. If the crop does not experience a certain level of water stress, bulbing would not be initiated. Additionally, if it does not receive enough water during bulb formation, bulbs will be of a smaller size and yield will consequently be lower. Irrigation water quality was raised as a very important issue by one of the growers. In case of having high salt content, onion yield would be dramatically reduced.

Most growers consider compaction, waterlogging and capping as the most influential soil issues affecting onion yield. Due to the shallowness of the crop, most problems would originate from disruptions in the surface and upper soil layer. Regardless of soil type, compaction was identified as the most significant problem. Waterlogging also represents a dramatic issue in soils or areas with defective drainage - sands and loamy sands are free of this risk. Waterlogging is linked to fungal diseases, weakening plants, restricting their development (yield reduction), and introducing contamination in storage (affecting quality).

Capping tends to appear on soils with some lime or clay content, and usually becomes a problem when rain falls shortly after drilling. It affects crop emergence and consequently plant density and uniformity. Other less frequent causes of yield reduction are acidity, stoniness, and high clay or content of organic matter. Lastly, the presence of stones on fields can cause marks and narrow bulbs.

Quality

Growers and interviewees from the packing industry agree that supermarkets require “round”, “neat”, homogeneous and size-specific bulbs. One of the most important focuses of quality checks in pack-houses is external appearance. Bulbs should not have any stains or colour variations on the skin; split skins or swollen base plates are not acceptable either. Internal defects, such as green shoots, discolouration or soft bulbs have a very important role in final product quality. Consistent bulb colour is second only to the importance of growing a highly uniform crop in terms of size and shape in growers’ priorities.

The tolerance of defects varies depending on the supermarket and the intended final product. Generally, it is linked to a percentage of a certain defect or the accumulation of several issues; however each retailer’s quality thresholds are kept confidential.

Packers classify internal and external bulb issues into ‘major’ or ‘minor’ defects. There is a low tolerance for major defects such as internal and external rots or breakdown, physical damage, staining, double bulbs, hollow necks and mould – usually caused by *Aspergillus* or *Penicillium*. There is a greater tolerance for minor defects, such as internal regrowth, external mechanical damage, *Thrips* damage, and weeping necks.

Continuity of supply is widely recognised as an important issue for both, supermarkets and processors. External colour and skin finish are not as important as having a single-centred bulb, according to interviewees from the processing industry. Usually bigger bulbs and sometimes specific varieties (with

a certain shape) are required for more efficient processing by machinery (e.g. cutting, peeling).

According to growers, the price they get for their crop varies from 50 £ t⁻¹ to over 300 £ t⁻¹. This depends on the size and quality of the bulbs, the final product, and the time of sale. In general, if supermarket standards are not reached, another market would need to be found for the crop, such as the processing industry (where the price might be reduced by 25%), or animal feed.

Factors affecting quality

Harvesting conditions and crop status at this point were raised as key determinants of storability and post-harvest quality by all the interviewees. It is very important, that bulbs are mature and partially dry. It is crucial for storehouse owners (farmers and members of the industry) that bulbs are free of any fungal or bacterial disease that could spread in store and spoil the production.

Onion post-harvest quality was recognized to be mainly linked to bulb health status, regrowth and storability by agronomist and packers; the latter is a compromise between dormancy in storage and emergency, as they are usually linked together. Other factors such as soil properties, weather conditions and water applications can also affect onion storability.

Soil texture has been recognized by growers as an important factor affecting post-harvest quality. This is the result of water dynamics and its retention. Waterlogging is linked to fungal diseases. These reduce yield and trigger rots causing significant losses in store. Some growers found that onions grown on sandy soils store better. In light soils water is easily drained. This allowed for a dry soil surface and the ability to keep bulbs away from water during the crop's last stage. In contrast, on heavier soils, which retain water for longer, bulbs could stay wet before harvest therefore negatively impacting storability. Agronomists identified compaction as one of the major issues affecting quality. This was followed by waterlogging, a restrictive soil horizon and high organic matter content. Stained bulbs are produced when the soil organic matter (OM)

content exceeds 20%. In cases of high OM in the soils, bulbs with thin skins are produced. Staining also occurs as the result of farming on silt and fine grain soils.

Clayey soils were also identified as being problematic by growers, agronomist and packers, because they stain onion skins. Soil particles remain attached to the outer bulb layers forming dark spots, these are considered to be external defects. The presence of stones on fields causes marks and narrow bulbs. Usually soils are de-stoned before drilling. Stones are left aside forming rows. Problems may occur when those lines coincide with the planted/drilled rows. High levels of organic matter, as well as clay content, tend to stain the skin, resulting in dark spotted bulbs.

Poor irrigation practice was highlighted by the three sectors as a potential cause of diminishing post-harvest quality especially in the case of over-irrigation. As in the case of late applications, water excess can cause bulbs to become spongy and soft and more prone to diseases.

After indicating the importance of bulb defects, interviewed growers were unequivocal in their aim of producing disease free bulbs of a specific size. However, quality standards are not always reached, which obliges growers to consider less demanding customers. Nevertheless, in some occasions higher profits can be made selling to household markets or food processors during certain periods, instead of to supermarkets.

Chapter 4. AquaCrop - model parameterisation for onion (*Allium cepa* L.) cv Arthur

This chapter presents the research approaches, methodology and results for the AquaCrop model calibration and validation for brown onion (*cv Arthur*) cultivation in the UK. The chapter first describes the criteria used for crop model selection, then the datasets required for model parameterisation, followed by a description of the model calibration and validation.

4.1 Introduction

Biophysical modelling is a quantitative method to predict the growth, development, and yield of a crop, given a set of genetic features and relevant environmental variables (Monteith, 1996). Crop growth models are often used as tools in farm management or for research purposes. Models can be used as tools in scenario analysis and planning in different seasons and locations (Steduto *et al.*, 2009, Hsiao *et al.*, 2009), helping finding optimal planting dates, cultivars, or water applications. An appropriate model could reduce the amount of treatments (and consequently trials) of an experiment. This allows more accurate experimental design and research cost saving (Whisler *et al.* 1986).

Steduto *et al.* (2009) distinguish two modelling approaches: scientific and engineering. The scientific approach uses laws and theory on physiology to generate the crop response to the environmental factors. Engineering models on the other hand combine more general, but well-established theory and empirical experiences. Usually, the latter focus on canopy or field scale, and can simulate a wide range of crops after suitable local parameterization (e.g. CropSyst, AquaCrop, DSSAT), whilst physiology based models have been developed for specific application to a single crop and apply physiological knowledge at a plant level (e.g. Oryza2000 for rice, CERES-Wheat, CERES-Maize for wheat and maize, respectively).

FAO AquaCrop is a canopy-level model which follows an engineering approach (Pasquale Steduto *et al.* 2009; Theodore C. Hsiao *et al.* 2009). The AquaCrop

model simulates crop response in terms of biomass, canopy cover, and yield, to water availability in daily time steps. It considers water fluxes and generates crop responses taking into account daily transpiration. Total biomass and harvestable yield production depends on crop parameters such as water response, stomatal conductance, canopy senescence and harvest index (Pasquale Steduto *et al.* 2009).

This model can be a very powerful tool to increase irrigation water efficiency, matching onion plant requirements to water inputs. It has been used to explore more efficient irrigation schedules in vegetables such as tomato in Italy (Rinaldi *et al.* 2011) and cabbage in Burkina Faso (Wellens *et al.* 2013) and extensive crops such as wheat in Canada and USA (Mkhabela & Bullock 2012; Nielsen *et al.* 2012) and maize in India and USA (Nielsen *et al.* 2012; Abedinpour *et al.* 2012). The results showed that the AquaCrop model can be used as a tool to advise farmers' on irrigation scheduling. Researchers agree that this model provides very accurate predictions considering the limited data requirements for parameterisation (Stricevic *et al.*, 2011, Andarzian *et al.*, 2011, Lin *et al.*, 2012).

The aim of this chapter is to select a suitable crop model, then calibrate and validate it for use on brown onions grown in the UK. To this end, the scientific literature was reviewed to find the most suitable crop model. In this study, AquaCrop model has been parameterized, calibrated, and validated for onions *cv Arthur* using a combination of experimental and field data.

4.2 Methodology

A review was conducted to identify existing available models to simulate onion crop response to environmental conditions. Those models were compared and their suitability assessed for the purpose of this research. The criteria used in the selection of a suitable model included daily time step simulation, water balance, irrigation and crop response to water inputs, actual vs. potential yield and canopy cover, harvestable yield production, and other input options regarding soil and crop characteristics.

A series of models were considered. From the scientific physiology-based ALCEPAS (C L M de Visser 1994), to engineering models such as CropSyst (Stöckle *et al.*, 2003), DNDC (DeNitrification-DeComposition, <http://www.dndc.sr.unh.edu/>), DSSAT (Decision Support System for Agrotechnology Transfer ,Hoogenboom *et al.*, 1995) and AquaCrop (Steduto *et al.*, 2009, and Raes *et al.*, 2009). Table 3 presents the features of models that were considered; further details about the models can be found in Appendix B. After reviewing the available models the AquaCrop was chosen as the most suitable model as it provided a daily response in biomass, canopy cover, and yield to climate inputs and irrigation. This model simulates in detail soil water movement and its availability and correlates it to crop stress.

Table 3 Model and features for the crop models reviewed. Y: Yes, N: No.

Model	ALCEPAS	AquaCrop	CROPGRO	CropSyst	De Visser and van den Berg, 1998	DNDC	Greenwood <i>et al.</i>, 2001	MOPECO
Daily time step simulation	Y	Y	Y	Y	N	Y		Y**
Water balance and crop response to water inputs	N	Y	Y	Y	N	Y	N	N
Actual vs. potential yield/canopy cover	N	Y			N	Y		N
Yield production	Y	Y	Y	Y	N	Y		N
Size distribution	N	N			Y	N		N
Fertilisation	N	Y	Y	Y	N	Y	Y	N
Soil characteristics	N	Y	Y	Y	N	Y		N
Previously used for onions/allium	Y	N	N	Y*	Y			
Model package includes onion parameters	Y	N	N	N	Y	Y		
Availability	N	Y	I	Y	N	Y	N	Y
Easy interface		Y		N		Y		
Easy parameterisation		Y		N		Y		
Contact with developers	N	Y	Y		N	N		Y

*Garlic, **crop water requirements estimation

In order to parameterize, calibrate and validate the AquaCrop model, first the relevant inputs data needed to be identified. The essential data set included location, climatic records, soil characteristics, crop characteristics, and irrigation and field management practices. These data were collected from trial data at an experimental field station in Suffolk, UK. During 2010, 2011, and 2012 several experiments were conducted in Broom's Barn (Higham, Bury St Edmunds, Suffolk) by Lacey & Ober (2012 and 2011) as part of an HDC (Horticultural Development Company) funded project FV 362a. The aim of their study was to investigate the effects of different irrigation schedules on *Rjjsburger* bulb onion husbandry, quality and storability. The data recorded as part of those experiments were then used to calibrate and validate the AquaCrop model in this study. A brief description of the experimental layout used at Brooms Barn, the data collected and how it was then used in this study is given below.

4.2.1 Experimental outline and crop data collection

Eight different irrigation treatments were tested in each experimental year. Climate, soil moisture content, crop development, pests, weeds and other aspects of the crop were recorded.

Eight irrigation treatments were conducted in 2010, 2011 and 2012, under a polytunnel. Those treatments were named A to H (Table 4). Irrigation events were triggered according to the available water content (AWC) within the rooting zone (Appendix C). Irrigation trials were readjusted after 2010 trials, slightly modifying the schedule through the season, and rejecting the poor performing/unsuitable schedules. Thus in 2011 and 2012, stress was induced during different stages of the crop.

Each irrigation treatment had three replicates (Appendix C.2 for plot layout). The experimental considered onions of the *Arthur* cultivar, at a targeted density of 52 plants per m². Onions were drilled and harvested on the dates shown in Table 5. The polytunnels' shelter were installed in in April/May (Table 5). After these dates, irrigation was the only water input. More details on the experiment are provided in Lacey & Ober (2011 and 2012).

Table 4 Irrigation regimes for the trials in Broom's Barn in 2010, 2011 and 2012 (Source: Lacey & Ober 2011; Lacey & Ober 2012).

2010		2011		2012	
A1	Typical	A2	Typical, end season stress	A3	Typical, end season stress
B1	Typical, no extra stress	B2	Typical with mid & end season stress	B3	Typical with mid & end season stress
C1	Typical, no extra stress, extended	C2	Typical with early & end season stress	C3	Typical with early & end season stress
D1	Less more often, no extra stress	D2	Less more often, no stress	D3	Less more often, no stress
E1	Less more often, no extra stress, extended	E2	Less more often, end season stress	E3	Less more often, end season stress
F1	Excess	F2	Less more often, mid & end season stress	F3	Less more often, end season stress, late irrig.
G1	Stress	G2	Less more often, early & end season stress	G3	Less more often, then typical, end stress
H1	No irrigation	H2	Stress all season	H3	Stress all season

Table 5 Drilling, harvesting and rain shelter installation dates for onions cv. Arthur in the experimental station Broom's Barn (Source: Lacey & Ober 2011; Lacey & Ober 2012).

Year	Planting date	Harvest date	Rain shelters installation
2010	18 th March	13 th September	28 th April
2011	21 st March	30 th August	19 th April
2012	20 th March	14 th September (treatments: E,F,G) 24 th September (treatments: A,B,C,D,H)	19 th May

Study site

The study site was located in Broom's Barns Research Centre (52.61741°; 0.566495°; 70 m asl), Suffolk, UK. This experimental station is located in one of the most important areas of onion production. The experimental trials were situated under polytunnels.

Climate data collection

Climate conditions were recorded under the polytunnel's shelter by an automatic weather station. This would measure daily temperature (max/min), rainfall (until polytunnel installation), relative humidity, radiation, and wind speed. Figure 9 shows the recorded mean monthly temperature, rainfall and reference evapotranspiration (ET_o).

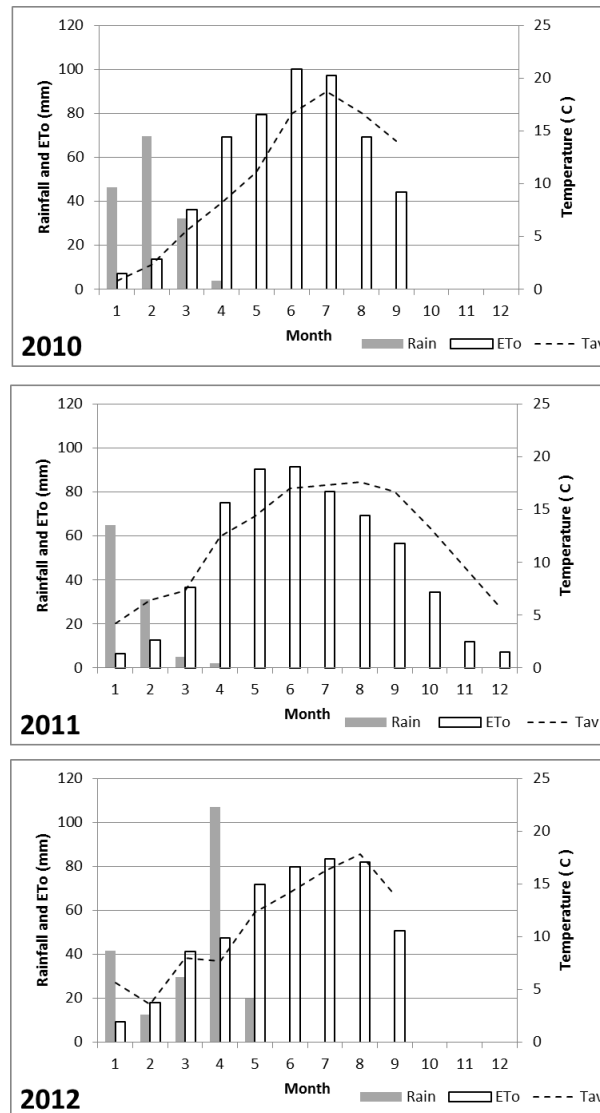


Figure 9 Mean monthly rainfall and ET_o (mm) and average temperature (°C) recorded in Broom's Barn Research Centre in 2010, 2011 and 2012 under the polytunnel.

Soil data

To simulate soil water movement and retention, information about the different soil horizons – including soil texture and thickness -, and the presence (if any) and depth of any restrictive layer (compaction) were required. Soil texture analyses established that the soils consisted of loamy sand (Lacey & Ober 2011; Lacey & Ober 2012). Hydraulic conductivity and soil water content at saturation (SAT), field capacity (FC), permanent wilting point (PWP), and total available water (TAW) depend on soil texture. FC and SAT were experimentally established in-field, following the methodology explained in section 2.6 used by Zekri and Parsons (1999). According to the soil water content at PWP and SAT the equivalent “soil texture” was determined (Allen *et al.* 1998) and PWP and TAW determined for that texture.

On the basis of the soil water content at saturation and field capacity, the trials’ soils were categorised as a mixture of sandy loam and loamy sand textures (Allen *et al.* 1998). For the modelling, three soil horizons of 0.1 m each were considered. This soil depth was chosen for the profiles, as soil water content was measured at the depths of 0.1, 0.2 and 0.3 m in each of the experimental plots. Sandy loam and loamy sand water hydrologic characteristics are shown in Table 6. FC and SAT measurements were compared to soil water content given for different soil textures and modelled soil texture decided by approximation.

Table 6 Soil moisture content at permanent wilting point (PWP), field capacity (FC), saturation (SAT) in %, and hydraulic conductivity at saturation in mm per day, for sandy loam and loamy sand soils (Allen *et al.* 1998).

	PWP (%)	FC (%)	SAT (%)	K _{SAT} (mm d ⁻¹)
Sandy loam	10.0	22.0	41.0	500
Loamy sand	8.0	16.0	38.0	800

Average soil texture for each irrigation treatment and each of their 0.1 m top layers are given in Table 7.

Table 7 Average soil texture for each soil layer and irrigation treatment (LS: Loamy sand; SL: Sandy loam).

Irrigation treatment	Soil texture		
	0-0.1m	0.1-0.2m	>0.2m
A	LS	SL	SL
B	LS	LS	SL
C	LS	SL	SL
D	LS	SL	LS
E	LS	LS	SL
F	SL	SL	LS
G	LS	SL	SL
H	LS	LS	SL

It has to be noted that due to the soil texture determination, uncertainty in the simulated water balance could arise.

Soil water data collection

Soil moisture content was recorded with capacitance probes (Decagon 10HS sensors) at depths of 0.1, 0.2 and 0.3 m every 15 min in each plot. The irrigation schedule was based on the calculation of water depletion based on those readings. The amount of water required in the root zone to bring the soil back to its field capacity is known as soil water depletion (Allen *et al.* 1998). The irrigation thresholds and application rates for each of the treatments are shown in Appendix C.

Crop data collection

Canopy cover estimations were made using light interception records, measured by a hand-held spectral radiometer (Skye Spectrosense 2) to determine the percentage of green cover at a specific point in each plot (Lacey & Ober, 2011). Measurements were conducted weekly. In 2010 measurements were taken 31, 61, 68, 76, 85, 92, 97, 105, 112, 119, 124, 132, 140, 52, and

181 days after drilling, and in 2011: 73, 85, 87, 102, 113, 127 and 143 days after planting. These data were used during the AquaCrop model calibration and validation stages. Root depth was estimated from the capacitance probe data, thus acquiring values of 0.1, 0.2 or 0.3 m (same as depth of moisture probes).

Lacey and Ober (2011; 2012) measured biomass through the growing season.. Plant biomass (fresh weight per plant) was determined approximately every 4 weeks. A sub-sample of 10 randomly selected plants per plot was weighed.

Final green yield was recorded for each of the treatments, as well as, vigour, fall-over, senescence and the effect of some pests and diseases.

Experimental yield records were given as tonnes of fresh green yield per ha and transformed into tonnes of dry matter (DM) per hectare by multiplication with a dry matter conversion factor determined experimentally (11-13%). Experimental yield is higher than the yield harvested on farms, therefore a correction factor of -15% was applied to the yield data following advice from Lacey (*pers comm*). In experimental trials, every bulb and small plant is collected; however, on commercial farm small bulbs (less than 40 mm) are left on the field. This diameter corresponds to the minimum that harvesters can lift.

4.2.2 Model description

The science literature was reviewed to find a suitable crop model capable of simulating crop growth, development and yield of onions. The criteria used for model selection are shown in Appendix B. The required characteristics included daily time step simulation, detailed water fluxes, crop response to available water, actual vs. potential yield and canopy cover, yield production, and input options regarding soil and crop characteristics. Considering these requirements, AquaCrop was identified as being the most suitable model for this study.

AquaCrop was developed adopting the methodology used in “FAO Irrigation & Drainage Paper no. 33, Yield Response to Water” (Doorenbos & Kassam 1979) later also adopted by FAO irrigation scheduling model CROPWAT (M. Smith

1992), where crop yield is estimated as a response to crop ET. AquaCrop is an accurate model, that preserves the original theory of FAO Paper no. 33, its simplicity and robustness (Steduto *et al.* 2012).

Fundamentally, the AquaCrop model consists of:

- Separating ET into its two components soil evaporation E and crop transpiration (Tr)
- Estimating Tr and E separation based on a simple canopy growth and senescence model
- Final yield Y is a function of final biomass (B) and harvest index (HI)
- Effects of water stress are separated in four components according to its effects on canopy growth, canopy senescence, Tr, and HI

The model determines growth on a daily bases according to Equation 3.

$$B=WP*Tr \quad \text{Equation 3}$$

Where B stands for biomass, Tr for transpiration and WP for water productivity. WP is defined as biomass per cumulative transpiration.

The model's soil-crop-atmosphere continuum is structured to include the following systems and components:

- The soil: water balance
- The plant: growth, development, yield processes
- Atmosphere: temperatures, rainfall, evaporative demand and CO₂ concentration

Figure 10 presents the main components of the continuum soil-plant-atmosphere, and the parameters determining plant response to them. A more detailed description of the model is available in Steduto *et al.* (2009) and Raes *et al.* (2009).

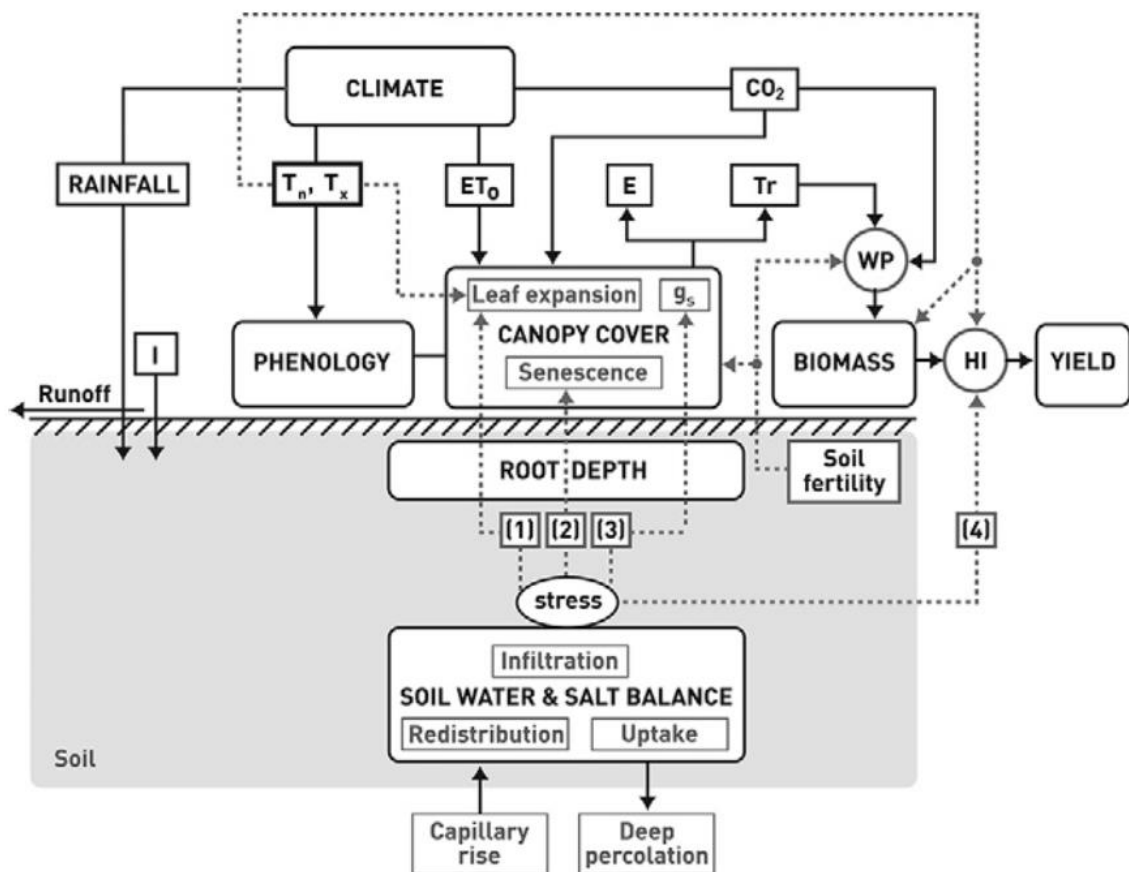


Figure 10 Chart of AquaCrop indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield [I, irrigation; T_n , minimum air temperature; T_x , Max air temperature; ET_0 , reference evapotranspiration; E , soil evaporation; Tr , canopy transpiration; g_s , stomatal conductance; WP , water productivity; HI , harvest index; CO_2 , atmospheric carbon dioxide concentration; (1), (2), (3), (4), different water stress response functions]. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. (Steduto *et al.*, 2009)

Figure 11 presents a detailed outline of the operations running within the AquaCrop model (Dirk Raes *et al.* 2011). Green CC development is determined by the factors: planting density, air temperature (given as growing degree days) and the effects of water and fertility stress. Daily transpiration Tr is given as a function of water deficit, causing stomatal closure, CC, ET_0 and the adjusted K_c

based on crop aging and/or senescence. Once Tr is known, B is estimated after considering negative factors affecting biomass production (temperature and soil fertility stress) and including WP adjusted in relation to CO_2 concentration and synthesized crop products. Finally yield is the result of HI , B and positive or negative stress affecting HI .

The fundamentals of the interactions and calculations of AquaCrop simulations are detailed in Raes *et al.* (2009); and Raes *et al.*(2011)

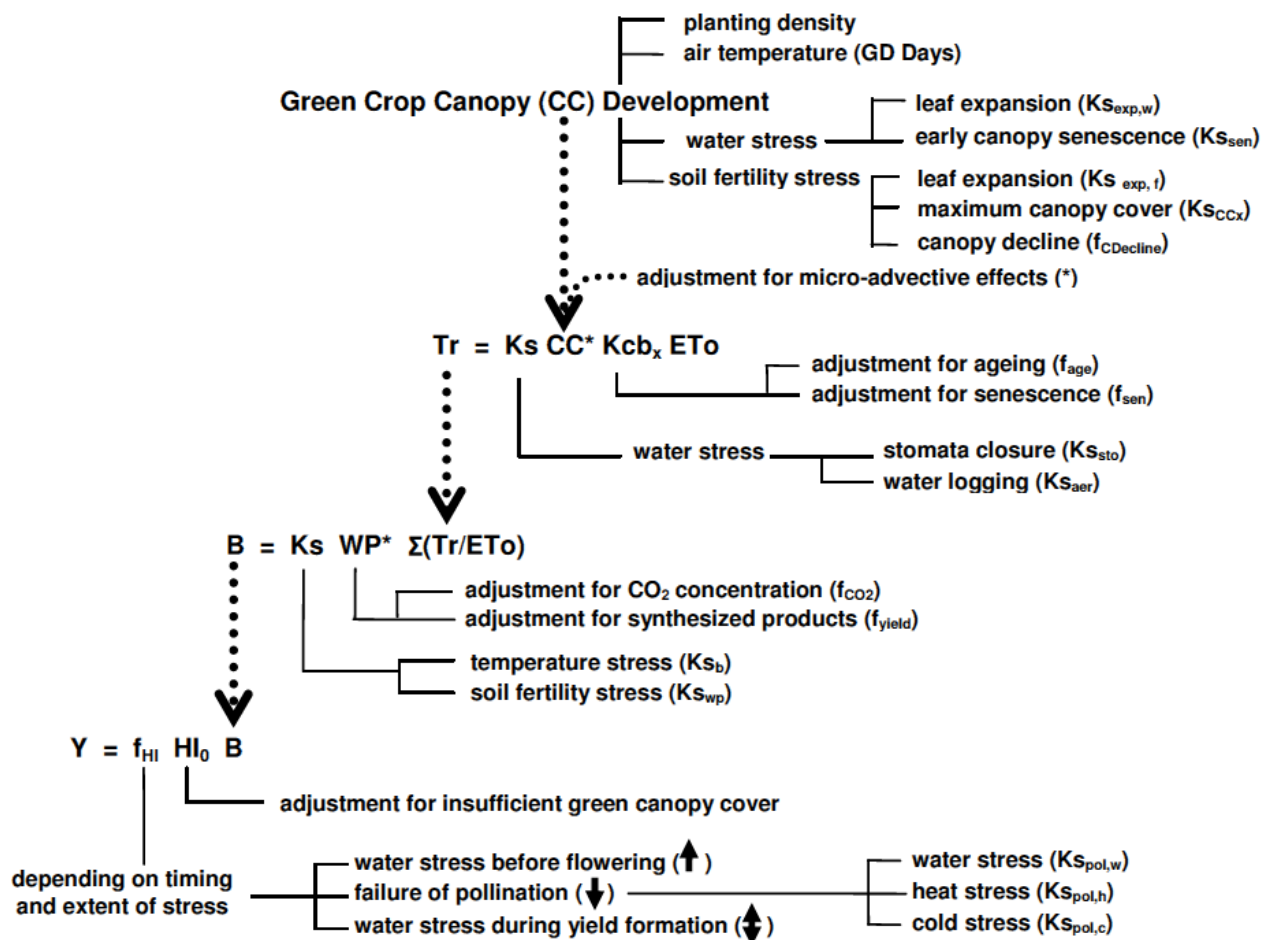


Figure 11 Schematic outline of the AquaCrop model operation (Raes *et al.* 2011)

The AquaCrop package incorporates crop files for certain crops (e.g. maize, wheat, potatoes, and sugar beet). However, no previous study has been conducted with AquaCrop for onion crop growth. Thus crop parameters had to be identified and the model calibrated and validated using experimental data.

Data required to parameterize the model consisted of crop and soil measurements comparable with the model's intermediate results, as well as climatic data and final yield and biomass. Canopy cover, biomass, and soil moisture content were used to assess the adequacy of the model.

In terms of crop definition, firstly, the crop type had to be specified. AquaCrop has specific data requirements and growth cycles depending on whether the crop is a fruit or grain producer, a leafy vegetable, root or a tuber crop. Crop characteristics such as lower and upper temperature limits, water stress tolerance (soil water depletion factors for canopy expansion stoppage, stomatal closure and canopy senescence), and response to fertility have to be established. Figures about root expansion (maximum rooting depth, and root water extraction pattern) and canopy growth (maximum canopy cover, and decrease during decline) were found in the literature and contrasted with experimental data.

Growing stages could be defined according to days or growing degree days (GDD). Time (in days) or GDD (in °C.d) determine plant emergence, achievement of maximum rooting depth, maximum CC, beginning of yield formation, start of senescence, and crop maturity. Crop response to water depends on the Water Productivity (WP), Harvest Index (HI), impacts on HI of growth under water restriction, and impacts caused by stomatal closure.

Planting date and plant density needed to be specified. Had any special land management practices taken place (soil bunds or mulches) it would be necessary to indicate this in the model; however, this was not the case in the present study. Irrigation inputs including application method (drip, sprinkler or surface), the depths applied, and their dates all were inputted into the model

4.2.2.1 Model calibration

AquaCrop was parameterized for onions *cv Arthur* using the data collected by HDC at the experimental station of Broom's Barns Research Centre.

AquaCrop was calibrated using the climatic and soil conditions recorded under the polytunnels. Six out of the eight irrigation treatments were simulated for 2010, and validated with the eight regimes in 2011, and 2012.

The model parameterization started considering irrigation regime 'F', 'excess'. This irrigation regime was considered optimal, leading to highest potential canopy cover and maximum yield. Irrigation was the most frequent and no water stress was allowed. The model calibration continued with the other treatments in 2010.

Crop parameters found in the literature were used in this stage. Then the specific conditions of the research station (drilling date, planting density, irrigation dates and weather conditions) were reproduced. Canopy cover, biomass, yield and soil moisture records were used to assess the adequacy of the model.

While calibrating the model, canopy cover, soil moisture and final yield simulated values were compared with the observed records. Crop parameters were adjusted for a better fit.

Irrigation treatments G1 and H1 were not considered. Total water inputs during the season were of 151 and 31 mm for these treatments, because rainfall was blocked by the tunnels, hence these treatments represent a very unlikely situation in the UK.

At irrigation schedule G1, 'stress' treatment in 2010, irrigation was applied to return to FC at deficit of 75% of AWC; and after bulb initiation half of the deficit was returned at 75% AWC. At regime H1, no irrigation was applied in 2010.

4.2.2.2 Model validation

After calibration, the model was validated using 2011 and 2012 data (A2, B2, C2, D2, E2, F2, H2, A3, B3, C3, D3, E3, F3, G3, and H3). The model's

adequacy and goodness of fit between observed and simulated yield, canopy cover and soil moisture data, were graphically and statistically assessed.

The root mean square error (RMSE), defined in Equation 4, was used to evaluate the adequacy of the model; it is defined by the following equation:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - O_i)^2} \quad \text{Equation 4}$$

Where S_i is the simulated and O_i the observed values.

This indicator is a measurement of the differences between individual simulated and measured (or observed) values. It gives an estimate of the accuracy of the model, thus, the smaller the value, the better (Loague & Green 1991).

RMSE incorporates the variance of the estimator and its bias (difference between this estimator's expected value and the true value being estimated). The units of this indicator are the same as for the considered parameter.

The robustness of the model was assessed with the model efficiency (ME) (Loague & Green 1991), see Equation 5.

$$ME = \frac{\sum_{i=1}^n (O_i - MO)^2 - \sum_{i=1}^n (S_i - O_i)^2}{\sum_{i=1}^n (O_i - MO)^2} \quad \text{Equation 5}$$

Where O_i and S_i are observed and simulated values, and MO is the average of the observed values. ME acquires values from infinite negative to 1. The closer it gets to 1, the higher the robustness of the model.

4.3 Results and discussion

The crop parameters (differing from the default values) for AquaCrop' after parameterization and calibration for brown onion *cv Arthur* are shown in Table 9.

Table 8 Parameters (different to the default values) resulting of the calibration of AquaCrop model.

Parameter	Value	Unit
Temperature requirements		
Base Temperature ¹	6	°C
Total crop cycle ²	1450	GDD
Crop response to soil water depletion		
Upper threshold for canopy expansion ³	0.3	soil water depletion fraction
Lower threshold for canopy expansion ³	0.65	soil water depletion fraction
Upper threshold for canopy senescence ⁴	0.92	soil water depletion fraction
Crop development		
from sowing to emergence ⁵	60	GDD
from sowing to maximum rooting depth ⁵	343	GDD
from sowing to start tuber formation ⁵	816	GDD
from sowing to start senescence ⁵	1263	GDD
from sowing to maturity (length of crop cycle) ⁵	1450	GDD
CGC for GGDays: Increase in canopy cover ⁶	0.07508	in fraction soil cover per growing-degree day
CDC for GGDays: Decrease in canopy cover ⁶	0.05365	in fraction per growing-degree day
Parameters affecting crop coefficient		
Crop coefficient when canopy is complete but prior to senescence ⁷	0.95	
Decline of crop coefficient as a result of ageing, nitrogen deficiency, etc. ⁸	0.8	%/day

Parameter	Value	Unit
Root development		
Maximum effective rooting depth ⁹	0.35	m
Shape factor describing root zone expansion ¹⁰	30	
Maximum root water extraction in top quarter of root zone ¹¹	0.057	m ³ water/m ³ soil.day
Maximum root water extraction in bottom quarter of root zone ¹¹	0.015	m ³ water/m ³ soil.day
Canopy Cover		
Effect of canopy cover in reducing soil evaporation in late season stage ¹²	60	
Canopy growth coefficient: Increase in canopy cover ¹³	0.01418	fraction soil cover per day
Canopy decline coefficient: Decrease in canopy cover ¹³	0.00545	fraction soil cover per day
Maximum canopy cover (CCx) ¹⁴	0.65	fraction of soil cover
Biomass production		
Building up of Harvest Index starting at root/tuber enlargement	57	Days
Water Productivity normalized for ETo and CO ₂ (WP*) ¹⁵	19	gram/m ²
Yield production		
Reference Harvest Index (HIo) ¹⁶	80	%

¹: Base temperature used for onion to estimate GDD by Bossie et al. (2009) was 6°C

²: Total crop cycle for the onions grown in the trials was of 1450 °Cd

³: Upper and lower threshold for canopy expansion correspond to AquaCrop's crop characteristics for a water stress tolerant crop (0.3 and 0.65 soil water depletion fraction). These values determine the range of RAW at which the canopy expansion is lower.

⁴: Upper threshold for canopy senescence for onions was established at 0.92 soil water depletion fraction, corresponding to a very high tolerance to water stress.

⁵: Crop stages length in GDD were determined from the climatic and crop development data provided by Lacey and Ober (2011, 2012)

⁶: Increase and decrease in canopy cover were indirect estimates from crop stages length and maximum canopy cover

⁷: Crop coefficient when canopy is complete but prior to senescence was modified between 0.9 (Piccini *et al.* 2009) and 1.05 (Allen *et al.* 1998), and a value of 0.95 gave appropriate answers for the measured evapotranspiration and soil water measurements

⁸: Decline of crop coefficient as a result of ageing was of 0.8%/day as given by Piccini *et al.* 2009

⁹: Maximum effective rooting depth was modified between 0.18 m to 0.40 m (according to Drinkwater and Janes (1955), and Greenwood *et al.* (1982) the majority of roots are concentrated here) and 0.35 m fit the soil water balance

¹⁰: Shape factor describing root zone expansion is 30, estimated from soil moisture readings by Lacey and Ober (2011, 2012)

¹¹: Maximum root water extraction in top and bottom quarters of root zone are values calculated by AquaCrop for a water uptake distribution of 40% - 30% - 20% -10% in the top, second, third and bottom quarters of the rootzone.

¹²: Effect of canopy cover in reducing soil evaporation in late season stage was fixed at 60% for a maximum canopy cover of 65%, taken into account Lopez-Urrea *et al.* (2009) determined an effect of 77% in crops where the maximum CC was of 72%

¹³: Canopy decline and growth coefficients are the results of the combination of maximum canopy cover (%) and the canopy growth and decline duration

¹⁴: Maximum canopy cover (CC_x) was 0.65 as measured by Lacey and Ober (2011, 2012)

¹⁵: Water Productivity normalized for ETo and CO2 (WP*) of 19 g/m², estimated using yield and irrigation input data from Lacey and Ober (2011, 2012)

¹⁶: Reference Harvest Index (Hlo) of 80% as mentioned in the literature and contracted with lab measurements

Onion growth and development was linked to GDD to unlink the model from calendar days. GDD were estimated as defined in Equation 6

$$GDD = (T_{max} + T_{min}) / 2 - T_{base} \quad \text{Equation 6}$$

In this case, the base temperature was of 6°C. Other studies used 4.4°C (Al-Jamal *et al.* 1999), 7°C (Piccini *et al.*, 2009), and 7.2°C (Knott 1988). The total cycle in those studies ranged between 1700 °C d and 2400 °C d (Al-Jamal *et al.* 1999) and 1200-1800 °C d. For onions grown in the UK total GDD was estimated using the base temperature 6°C and dates for planting and harvest together with the climatic data recorded at the experimental station.

Onion development in GDD was contrasted with the literature and the results of the UK growers' survey (Chapter 3). GDD until emergence were 60 °C d; slightly lower than the estimates of Finch-Savage & Phelps (1993) of 68.6-77.5, but similar to growers' responses when translated into days (about 40-50 days).

The approximate length of the cycle in days fell between the crop's length given by Allen *et al.* (1998) for Mediterranean and semi-arid conditions (150-210 days), Martín de Santa Olalla *et al.* (2004) (150 days), Lopez-Urrea *et al.* (2009) (138 days) for onions grown in Spain, and was very similar to the estimates of (Piccini *et al.* 2009) for Texas conditions (190 days).

Kc value of 0.95 at maximum coverage was greater than values of 0.85-0.9 given by Piccini *et al.* (2009); but lower than values given by Bossie *et al.* (2009), Martín de Santa Olalla *et al.* (2004), and Allen *et al.* (1998) (0.99, 1, and 1.05). The decline of Kc as a result of crop senescence was 0.8% per day.

Piccinni *et al.* (2009) established approximately the same daily reduction in their observations.

Onions are characterized as having a shallow root system. Usually, root penetration does not exceed 0.76 m (Drinkwater and Janes, 1955). However, most of the roots are concentrated in the top 0.18 m or 0.40 m, according to Drinkwater and Janes (1955) and Greenwood *et al.* (1982), respectively. For this study the value 0.35 m was used.

According to Lacey & Ober (2011, 2012) average maximum CC ranged between 60-65% of the soil cover; exceptionally 70% of CC was reached in 2012 for a few treatments. Lopez-Urrea *et al.* (2009) recorded maximum CC values of 72% in Spain. However, CC depends on plant density and general crop status. A conservative approach using the figure of 65% was used in this model.

Whilst harvest index (HI) can increase to 89% (J. L. Brewster 2008) after plants' fall-over, when the crop has dried completely; HI was set at 80% in the present case, as the model simulated only to the point of maturation, not subsequent drying.

Previously mentioned parameters were extracted from the literature and experimentally established by Lacey and Ober (2011, 2012). The rest of the parameters could not be found in the literature and were therefore established during the model calibration phase. CC and yield production were the variables used in the calibration of the model. The model adequacy was assessed by comparing the observed with the simulated variation in soil water content. Figure 12 shows soil moisture content in the root zone. The individual reading of the capacitance probes installed in treatments A and B are plotted (black continuous lines) against the simulated (dashed grey) values for the calibration period of 2010.

Soil water content is given in mm of water in the crop's root zone. The root zone considered in the observed records is 0.1, 0.2 or 0.30 m. However, in the

model, daily soil water content values are given, using 0.01 m steps from 0.20-0.35 m. One of the probes installed in plot A malfunctioned, hence only two observations were available.

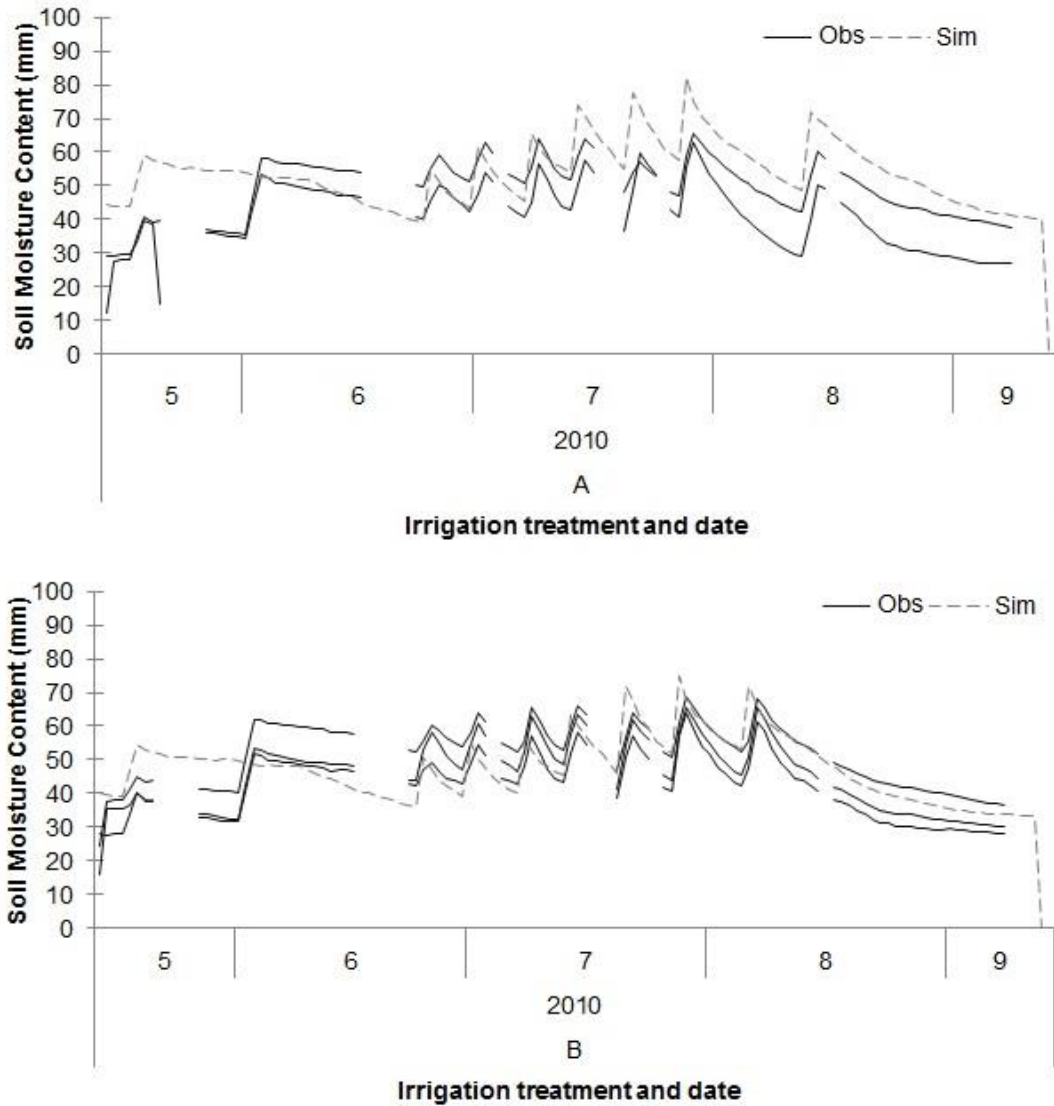


Figure 12 AquaCrop model simulated and observed soil moisture content (mm) in the root zone in the plots under irrigation treatments A and B in 2010 for the months May (5) to September (9).

Figure 13 presents observed and simulated CC as measurements were undertaken in 2010.

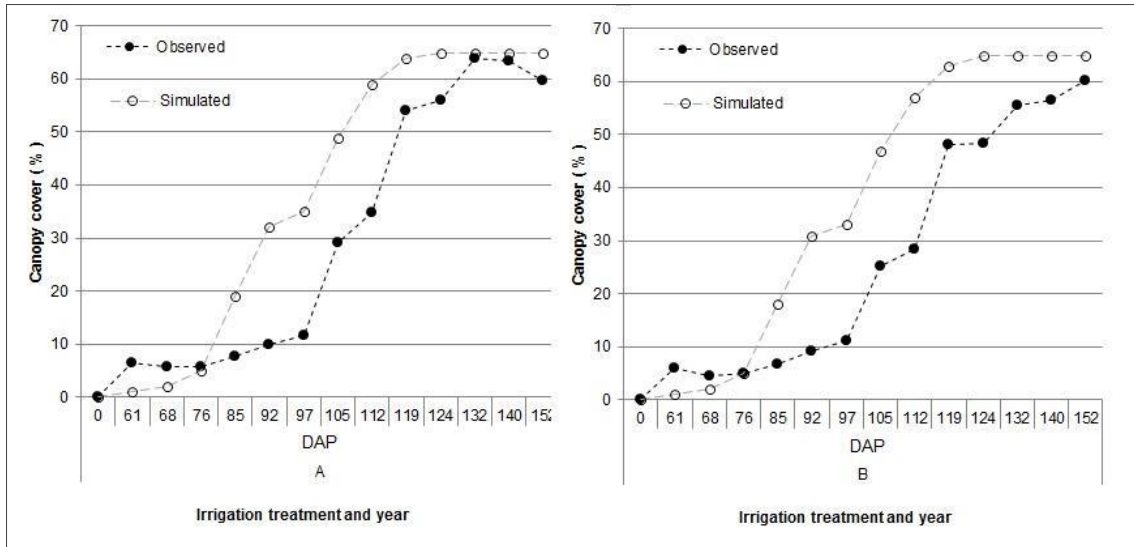


Figure 13 AquaCrop simulated and observed canopy cover (CC) for the given days after planting (DAP) selected in irrigation regimes (A and B) in 2010 at Brooms Barn.

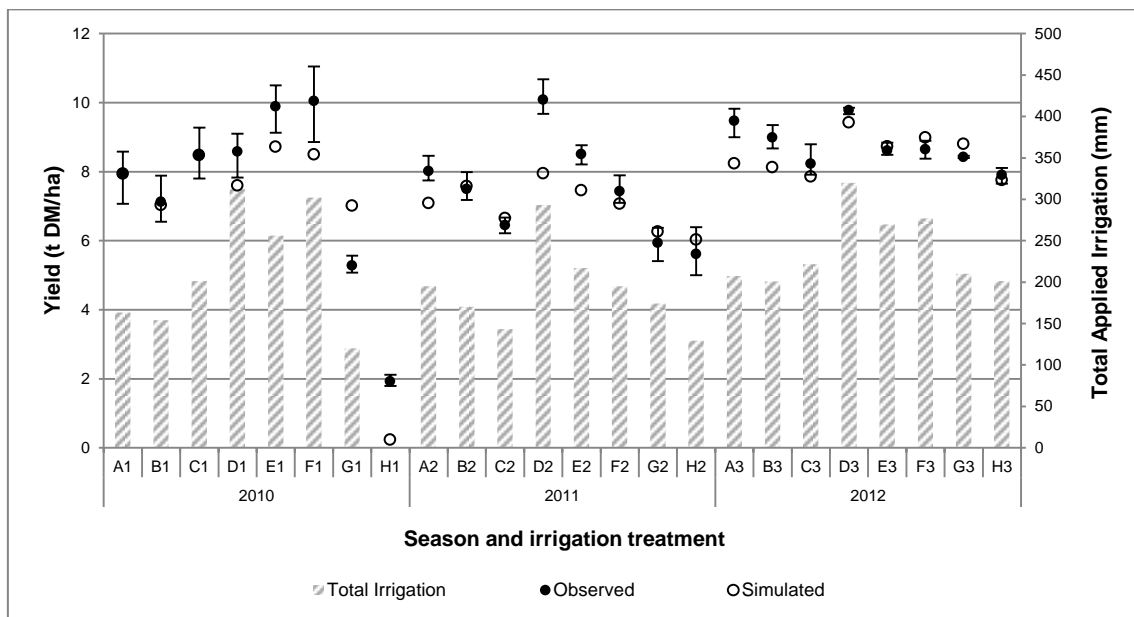


Figure 14 AquaCrop observed and simulated onion yield (t of DM per ha) and total irrigation depth for the different irrigation regimes in Brooms Barn experimental station in 2010, 2011, and 2012. Error bars show maximum and minimum observations.

Table 10 and Figure 14 present the observed and the simulated yield (t DM ha⁻¹) for the model calibration (season 2010) and model validation (2011 and 2012).

Table 9 Average, maximum and minimum observed yield in 2010, 2011, and 2012 in irrigation treatments A1-H3, maximum difference between treatment observations, simulated values, and difference between simulated yield and average observations.

Year	Treat.	Max t DM ha ⁻¹	Min t DM ha ⁻¹	Average t DM ha ⁻¹	Diff (max-min) t DM ha ⁻¹	Sim t DM ha ⁻¹	Diff Sim-Av Obs t DM ha ⁻¹
2010	A1	8.58	7.07	7.95	1.51	7.93	-0.02
	B1	7.89	6.55	7.12	1.34	7.03	-0.09
	C1	9.28	7.81	8.46	1.47	8.47	0.01
	D1	9.1	7.83	8.58	1.27	7.59	-0.99
	E1	10.5	9.13	9.88	1.37	8.72	-1.16
	F1	11.05	8.86	10.05	2.19	8.49	-1.56
	G1	5.56	5.07	5.27	0.49	7.01	1.74
	H1	2.12	1.79	1.92	0.32	0.23	-1.69
2011	A2	8.46	7.74	8.01	0.72	7.08	-0.93
	B2	7.99	7.19	7.49	0.81	7.58	0.09
	C2	6.67	6.22	6.45	0.45	6.65	0.2
	D2	10.68	9.68	10.08	1	7.95	-2.13
	E2	8.77	8.21	8.51	0.55	7.45	-1.06
	F2	7.89	7.1	7.42	0.79	7.06	-0.36
	G2	6.38	5.41	5.93	0.97	6.25	0.32
	H2	6.39	5	5.61	1.39	6.02	0.41
2012	A3	9.82	9	9.47	0.82	8.24	-1.23
	B3	9.36	8.68	8.99	0.68	8.13	-0.86
	C3	8.8	7.92	8.22	0.88	7.85	-0.37
	D3	9.86	9.67	9.77	0.19	9.42	-0.35
	E3	8.84	8.49	8.61	0.36	8.73	0.12
	F3	8.9	8.37	8.64	0.53	8.99	0.35
	G3	8.46	8.4	8.42	0.06	8.8	0.38
	H3	8.11	7.66	7.9	0.45	7.75	-0.15

Figure 15 presents the relationship between simulated and observed yield. In this graph, three observations correspond to one simulated value, because each observed value corresponds to one of the three repetitions of the irrigation regime.

The model showed a very good capacity to simulate water content in the rootzone in response to irrigation and crop transpiration (Figure 12 and Appendix D for complete data set). Its ability to then simulate crop development (measured as CC) was also good as showed in Figure 13 and Appendix D. Consequently, a good match with observed yield values was achieved.

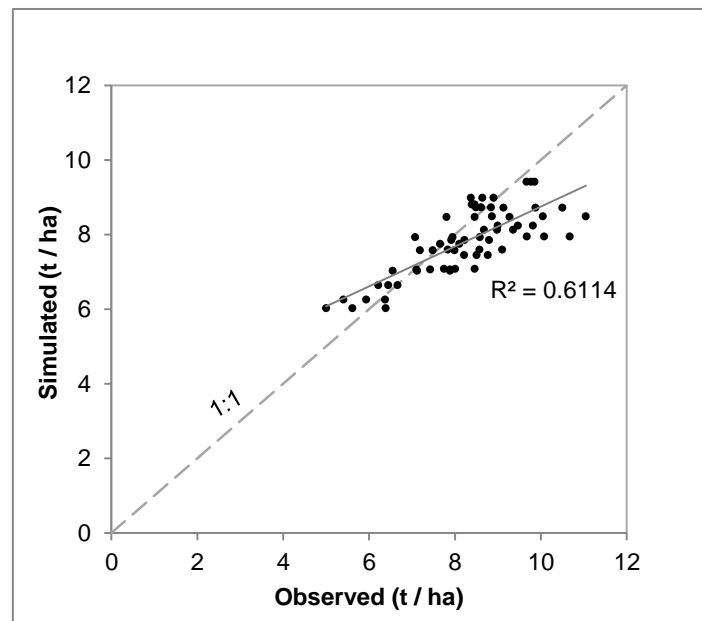


Figure 15 Linear correlation of simulated against observed yield (t/ha) for the irrigation treatments included in the AquaCrop model calibration and validation .

Table 10 presents the results for the RMSE and ME, as well as the standard deviation (SD) of the observed yield records. The estimations are shown by years and for all years combined. RMSE varies between 0.64 and 1.06 t DM ha⁻¹, which corresponds with the range of standard deviation (0.62-1.43). ME values range between -0.06 to 0.52. Overall, the model performance is good, with a close correlation between simulated and observed yield (Figure 15).

Table 10 Calculated RMSE (t DM ha⁻¹), ME, and standard deviation of the observed data (t DM ha⁻¹) for each season and for the complete dataset .

Year	RMSE (t DM ha ⁻¹)	ME	Std dev (t DM ha ⁻¹)
2010	1.06	0.19	1.18
2011	1.03	0.52	1.43
2012	0.64	-0.06	0.62
Total	0.92	0.48	1.28

The AquaCrop model simulated the ‘typical’ irrigation schedule better than the treatments ‘Less more often’. The simulated yield, when irrigation supplied enough water to get the soil back to FC at a deficit of 50% of the AWC (‘typical’), was better than when the trigger deficit was of 25% (‘less more often’ regimens), with the exception of 2012.

In the cases in which the simulated canopy expansion took place more slowly than in the experimental trials (although maximum CC was eventually reached), final yield was inevitably diminished.

The simulated onion crop is more sensitive to this condition than the experimental trials. Although enough total water was applied during quick growth stages, the model was not able to simulate optimal transpiration rates. In AquaCrop crop biomass (ergo also CC) depends on transpiration; if soil moisture content does not allow maximum transpiration, maximum growth and canopy development will not be reached. This agrees with studies relating water reductions during the canopy development with declines in yield (Doorenbos & Kassam 1979; Kadayifci *et al.* 2005).

Treatments E1, D2, and E2 show that the modelled response to low applications (10-13 mm) is poor compared to applications of 25 mm, whilst the best model fits were achieved, when irrigation applications consisted of larger amounts (20-27mm).

In practice, under water stress conditions, onion plants tend to deepen their root system and use water from deeper soil layers. Onion roots can reach up to 80 cm depth (Jovanovic and Annandale, 1999; Drinkwater and Janes, 1955).

However, in this model, plants' water uptake occurs only in the top 35 cm. Thus leading to early crop decay, as the upper soil layer runs out of water. This is the case for treatments G1 and H1, and the reason these scenarios are not considered in this study.

In the calibration and validation of the model, it was assumed that fertilisation rates were optimal and equal on all the treatments. It should be taken into account, that the crop was grown under polytunnels. This could have affected ET rates as well as crop light interception, both of which are cited by Lercari & Deitzer as being very important for bulb initiation (1987).

Using the calibration settings and following validation, the AquaCrop model could now be used to study different onion crop response to different soil and irrigation scenarios.

Chapter 5. AquaCrop - model parameterisation for onion (*Allium cepa* L.) cv Arthur

The aim of this chapter is to assess the effects of irrigation non-uniformity on UK onion production (yield) to inform discussions on the potential application of precision irrigation. Therefore the effects on yield of uniform irrigation applications will be compared to non-uniform irrigation, for a set of agroclimatic conditions and contrasting soil types. The effects of irrigation non-uniformity on yield were simulated using the FAO AquaCrop model, previously parameterized (Chapter 4). Scenarios were defined to include two different soils (sandy and light sandy loam), and five different climatic years (extreme wet, average wet, average, average dry, and extreme dry).

5.1 Introduction

Rainfall in the UK is very variable (spatially and temporally) (Bigg 1991; Biggs & Atkinson 2010; Kendon & Pior 2011). Research on atmospheric circulation patterns have linked the British Islands' patterns of daily precipitation to airflows (Bonele & Sumner 1992; Biggs & Atkinson 2010). This variability affects river and groundwater recharge, floods and run off patterns, and has important impacts on environment and farming systems (Arnell et al. 1990; Segond et al. 2007; M. R. Jones et al. 2013). Extreme events and unpredictable weather conditions have been shown to affect UK crop production. Climatic conditions (droughts, and wet periods) affect yield, causing annual variability, sometimes, as a consequence of the spread of diseases (Mackay *et al.* 2011).

This climatic variability makes the need for irrigation variable also, depending on season, and field location. In addition to weather conditions (radiation, temperature, RH, ETo, wind speed, rainfall, etc.), soil properties (water holding capacity) are used to estimate crop water requirements (Allen *et al.* 1998). Several crops are routinely irrigated in the UK, in particular field vegetables, which are second only to potatoes in terms of irrigated area and crop value (E K Weatherhead 2006).

This thesis focuses on the variability of onion yield. As presented in chapter 3, national onion production is mainly concentrated in East and West Anglia, with some extra production areas in Kent and Worcester. Crop growth, development and yield are the results of the interactions of genotype, agronomic practices and pedo-climatic conditions (Hay & Walker 1989). In onion cropping, marketable production is a compromise between yield and size (C.L.M. de Visser & Van den Berg 1998) which is very variable (Marino *et al.* 2013). Onion properties such as pungency (Yoo *et al.* 2006), nitrogen and sulphur requirements (McCallum *et al.* 2005), and water requirements (Kumar *et al.* 2007; Martín de Santa Olalla *et al.* 2004) can be affected by environmental conditions. Agronomic practices (fertilisation, irrigation, planting date, plant density) on the other hand have had a proven effect on plant characteristics (biomass, leaf area index), yield and its quality (Martín de Santa Olalla *et al.* 2004; Hay & Walker 1989; McGeary 1985; Hatridge-Esh & Bennett 1980; Bleasdale 1959).

According to Stafford (1996), crop non-uniformity is a result of spatial and temporal variations in soil structure and fertility, pest and diseases, irrigation and fertilization application. The concept of meeting the needs of individual plants or managing zones independently led to the development of precision farming. This involves targeting the inputs of arable crop production according to its requirements on a localized basis (Stafford, 1996).

The most commonly used irrigation application systems in onions grown in the UK (Chapter 3) are linear moves and booms fitted to the end of a hose-reel. Both irrigation application systems consist of a boom fitted with a series of sprinklers along a steel or aluminium pipe that travels down the field without rotating. Booms consist of a single drive unit up to 40 m, and linear moves are formed by a number of spans up to 1500 m (Figure 16).



Figure 16 Hosereel fitted with a boom (upper photo) and linear move (lower photo) irrigation application systems on onions, Elveden (2012).

The aim of this chapter is to predict the effects of irrigation non-uniformity on UK onion production (yield) to inform discussions on the potential application of precision irrigation. Non-uniform irrigated cases were compared with optimal conditions. The effects of this non-uniformity on yield were evaluated with the FAO AquaCrop onion-parameterized model using different soils and under different weather conditions for the UK onion growing areas. Scenarios were ran combining two different soils (sandy and light sandy loam), five different climatic years (extreme wet, average wet, average, average dry, and extreme dry), and two sprinkler irrigation methods (boom and linear move). These were then contrasted with *reference* conditions.

5.2 Methodology

Using the parameterized AquaCrop model (Chapter 4), a set of scenarios were defined and then used to assess the impacts of irrigation variability on onion yield. The scenarios reflect five contrasting agroclimatic years and two contrasting soil types (Table 11). These were simulated using the AquaCrop model, initially assuming for ‘uniform’ irrigation, and then repeated for ‘non-uniform’ irrigation. The ‘non-uniform’ irrigation simulations considered two types of application method; a hose reel fitted with a boom and a linear move irrigation system.

Table 11 Modelling scenario : combination of 5 agroclimatic conditions, 2 soil types, and uniform and non-uniform irrigation.

Agroclimatic condition	Soil type	Modified input: Irrigation		Evaluated Output
Extremely wet	Sand	Uniform	Non-uniform boom / linear move	Onion yield
	Sandy loam	Uniform	Non-uniform boom / linear move	Onion yield
Average wet	Sand	Uniform	Non-uniform boom / linear move	Onion yield
	Sandy loam	Uniform	Non-uniform boom / linear move	Onion yield
Average	Sand	Uniform	Non-uniform boom / linear move	Onion yield
	Sandy loam	Uniform	Non-uniform boom / linear move	Onion yield
Average dry	Sand	Uniform	Non-uniform boom / linear move	Onion yield
	Sandy loam	Uniform	Non-uniform boom / linear move	Onion yield
Extremely dry	Sand	Uniform	Non-uniform boom / linear move	Onion yield
	Sandy loam	Uniform	Non-uniform boom / linear move	Onion yield

The results of the UK onion industry survey (Chapter 3) were used to identify most important growing regions, soils, irrigation practices, planting dates and

plant density, and harvesting dates. With this information and climatic data from UK weather stations, the following scenarios were defined.

5.2.1 Defining model scenario

In order to establish a set of modelling scenario, a contrasting set of agroclimatic conditions, soils types and cropping practices were defined.

Climatic conditions: 5 different years

Weather stations for which historic data (from 1961 onwards) were available within the main UK onion growing areas (East Anglia, Lincolnshire, Cambridgeshire, Bedfordshire, and Kent) were identified. Daily minimum and maximum temperature, rainfall, and where available radiation, wind speed, and relative humidity (RH), were extracted from weather stations based in Norfolk, Suffolk, Cambridgeshire, Bedfordshire, and Lincolnshire.

In order to compare the agroclimate for the five different locations and their inter annual variation, the variable potential soil moisture deficit (PSMD) was estimated. PSMD is an agroclimatic indicator based on a simple water balance model, that has previously been used to assess irrigation needs across different regions (Rodríguez Díaz *et al.* 2007; and Knox *et al.* 2010). The advantage of this indicator compared to others, is that PSMD takes into account daily differences between rainfall and ETo, considering seasonal distribution. PSMD is estimated as the cumulative daily differences between water input and output (rainfall and ETo). Daily rainfall values (mm) are subtracted from the previous day total, whilst ETo is added to it (Kettlewell *et al.* 2006).

$$PSMD_i = PSMD_{i-1} + ETo_i - R_i \quad \text{Equation 7}$$

Where $PSMD_i$ is the PSMD on day i , $PSMD_{i-1}$ is the PSMD on the $i-1$, and ETo_i and R_i are evapotranspiration and rainfall on day i .

Usually, in the UK the PSMD during winter is zero, as rainfall exceeds ETo. It then starts increase during Spring, when daily ETo values are greater than precipitation. Maximum PSMD (PSMD_{max}) is usually reached in summer (July-August). During autumn, when daily rainfall starts to exceed ETo, PSMD starts to decline and eventually returns to zero.

In order to estimate annual PSMD_{max} for the given periods and locations, daily values of ETo and rainfall data were required. The available data set consisted of daily maximum and minimum temperatures for most of the period 1961-2011. Relative humidity (RH), wind speed and radiation (sunshine hours) data were only available for the years 1989-2006 in one of the stations (Cambridge). Therefore ETo was estimated using the adjusted Hargreaves method. This consists of calculating ETo using two different methods: Penman-Monteith (Allen *et al.* 1998) and Hargreaves and Samani (Hargreaves & Samani 1982). The Penman-Monteith method (PM) requires data that are not available for all the stations, while the Hargreaves and Samani method (HS) requires only daily minimum and maximum values. The correlation between both methods' ETo results was to found and then applied to HS results to obtain better estimates.

The FAO has adopted the Penman-Monteith method as a global standard for ETo estimation (Allen *et al.* 1998). This is an accurate method (Equation 8), and as such, it requires a wide range of climatic data. In order to calculate daily ETo using Penman-Monteith's equation, daily air minimum and maximum temperature, humidity, wind speed and radiation are required.

$$ET_o = \frac{0.408 \Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad \text{Equation 8}$$

Where:

ET_o: reference evapotranspiration (mm day⁻¹),

R_n: net radiation at the crop surface (MJ m⁻² day⁻¹),

G: soil heat flux density (MJ m⁻² day⁻¹),

T: air temperature at 2 m height (°C),

u_2 : wind speed at 2 m height (m s^{-1}),
 e_s : saturation vapour pressure (kPa),
 e_a : actual vapour pressure (kPa),
 $e_s - e_a$: saturation vapour pressure deficit (kPa),
 Δ : slope vapour pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$),
 γ : psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$).

The Hargreaves and Samani (1982) method (Equation 9) is an empirical method which needs fewer parameters (only daily minimum and maximum temperature).

$$ET_o = 0.0135K_T * (T + 17.78)(T_{min} - T_{max})^{0.5}R_a, \quad \text{Equation 9}$$

where

ET_o : reference evapotranspiration (mm day^{-1}),
 K_T : is 0.162 for interior regions and 0.190 for coastal regions
 T : average temperature ($^\circ\text{C}$)
 T_{min} : minimum temperature ($^\circ\text{C}$)
 T_{max} : maximum temperature ($^\circ\text{C}$)
 R_a : extra-terrestrial radiation (mm d^{-1}).

Daily ET_o was estimated using Penman-Monteith and Hargreaves methods for Cambridge's station using weather data from 1961 to 2011. ET_o resulting from the use of both methods were correlated showing following regression presented in Equation 10.

$$ET_{o_{PM}} = 0.9702 * ET_{o_{HS}} + 0.3177 \quad \text{Equation 10}$$

where $ET_{o_{PM}}$ and $ET_{o_{HS}}$ stand for ET_o estimated using Penman-Monteith and Hargreaves and Samani formulas. This equation was used to estimate the daily ET_o for all those days in which only temperature data were available.

After calculating daily ETo values, the daily PSMD at each site was calculated by combining the ETo and rainfall data (Equation 7). The maximum annual PSMD in each year was then calculated and used to rank the individual climate years (Figure 16) In order to have a range of climatic conditions representative of the UK onion growing area, it was decided to choose extreme and average dry and wet conditions, and an average year. The driest, average dry, average, average wet, and the wettest years were chosen according to their order in the ranking.

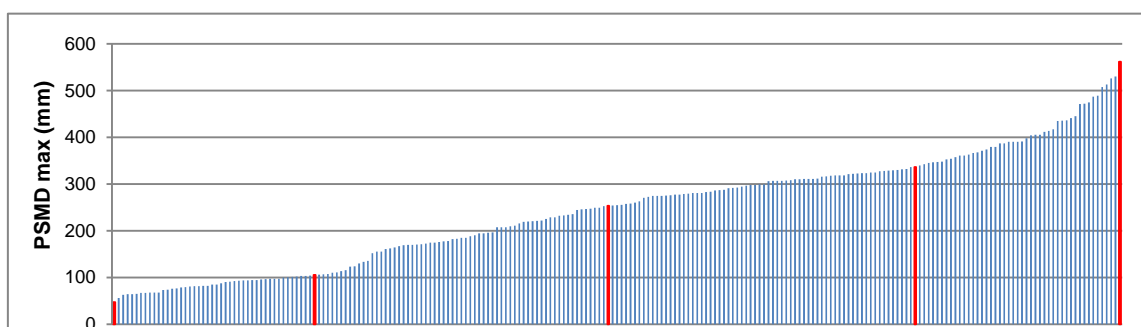


Figure 17 Ranked PSMD_{max} for the locations (Bedfordshire, Cambridgeshire, Norfolk, Suffolk, and Lincolnshire) for the years 1961-2011.

Figure 17 shows the ranked PSMD_{max} with highlighted bars for the chosen years. The chosen years corresponded to the 0%, 20%, 50%, 80%, and 100% of the probability of exceedance. The only prerequisite for crop modelling was that the selected years had a minimum GDD from March to September of 1425°C (seasonal AquaCrop onion requirement to complete a crop cycle).

The years selected and the locations of the weather stations where these records were taken, representing the ‘wettest’, ‘average wet’, ‘average’, ‘average dry’, and ‘driest’ years occurring in the UK main onion growing areas are shown in Table 12.

Table 12 Summary of the selected weather stations and climate years used for defining each agroclimate scenario.

Climate year	Weather station	Year	Location (latitude, longitude)	PSMD _{max} (mm)
Wettest	Buxton (Norfolk)	1968	52.755018°, 1.308674°	62
Average wet	Brooms Barn (Suffolk)	2002	52.260955°, 0.565775°	105
Average year	Silsoe (Beds)	2004;	52.009833°, -0.425666°	255
Average dry	Cambridge (Cambs)	1984	52.205950°, 0.121741°	340
Driest	Silsoe (Beds)	1976	52.009833°, -0.425666°	562

Soils: 2 different soils

The literature review and industry survey (Chapter 3) helped to identify the most commonly used soils for onion cultivation in the UK. The preferred soil textures rank from sand to light sandy loams. Consequently, the chosen soils for the scenario simulation were a deep sandy soil and a deep light sandy loam; Table 13 presents their typical characteristics.

Table 13 Characteristics of the sandy and light sandy loam soils.

	Sand ¹	Light Sandy Loam ²
Thickness (m)	4.0	4.0
Volume (%) at saturation	36.0	39.5
Volume (%) at field capacity	13.0	19.0
Volume (%) at wilting point	6.0	9
Ksat (mm / day)	1500.0	650
Readily evaporative water from top layer (%)	2	7
Restricting soil layer inhibiting root zone expansion	No	No

¹ Average value for sand ranks (Allen *et al.* 1998)

² lower values for the rank given for sandy loam (Allen *et al.* 1998)

Cropping practices

The planting date was the same for both soils and the different climatic conditions. March 1st was chosen for all simulations as this matches closely with the growers' planting target date based on the industry survey.

Once scenarios soil x climate were established, and irrigation requirements were identified (uniform irrigation), the required input files to run AquaCrop had to be created. An outline of the scenarios generated and required input files for the model are shown in Figure 18.

The soils and climatic conditions were common for uniform and non-uniform applied irrigation. Each of the non-uniform irrigation combinations would be run 100 times with the AquaCrop model.

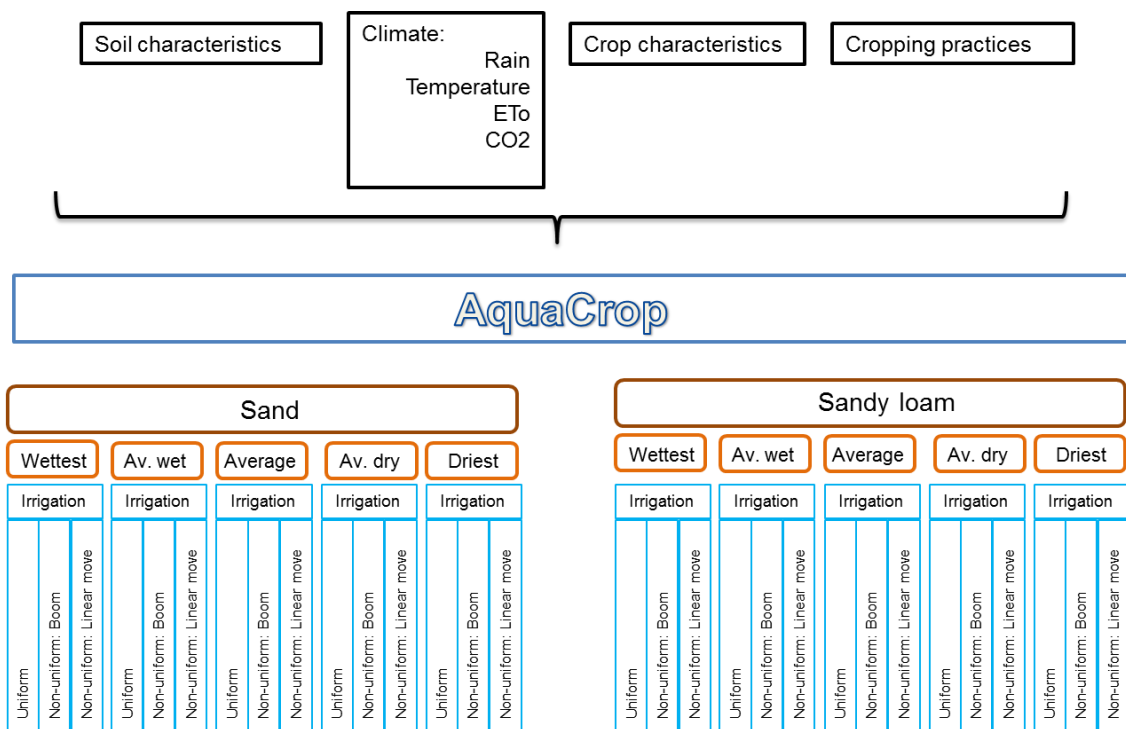


Figure 18 Schematic outline of the AquaCrop scenario modelling including input files and scenarios used to assess the impacts of soil, climate and irrigation equipment on onion yield.

In order to run these scenarios, AquaCrop needed a series of input data files: Soils, climate, crop and irrigation.

The climatic files consisted of ETo, rainfall and temperatures values of the previously chosen years. CO₂ was kept constant and equal to 380 ppm (average CO₂ atmospheric concentration for 2010 according to the Earth System Research Laboratory <http://www.esrl.noaa.gov/gmd/>) for all the

simulated seasons. The soil files used consisted of the previously mentioned characteristics Table 13.

The final crop parameters were the result of the calibration and validation of AquaCrop for onions grown in the UK (Chapter 4). The assumed planting date was 1st March.

Uniform irrigation

The simulated irrigation schedule represented the schedule recommended by most agronomists which was corroborated by the interviewed growers. This consists of the application of the following water depths (mm) after reaching the trigger soil moisture deficit SMD (mm) (Table 14). The irrigation triggers vary for different water retention capacities (dependent on the soil's texture) and crop stages.

Table 14 Reference irrigation schedule: soil moisture deficit (SMD) triggering irrigation and recommended application depth for sandy and light sandy loam

Soil texture	During canopy development	After bulbing
Sandy	16 mm at 16 mm SMD	23 mm at 23 mm SMD
Light sandy loam	23 mm at 23 mm SMD	29 mm at 29 mm SMD

Regardless of soil texture, no irrigation should be applied in the two weeks before harvest.

Seasonal irrigation requirements were estimated using the AquaCrop model with the *irrigation schedule generation* option enabled. First, the model was run for the given climatic conditions with the first irrigation triggers (16 and 23 mm). The entire crop cycle was irrigated following the initial schedule. The simulated date at which the crop changed its stage was used to change the irrigation trigger in the definitive irrigation schedule. The results comprised a series of dates on which the above specified depths (16, 23 and 29 mm) were applied for the allowable depletion of 16, 23 or 29 mm.

Non-uniform irrigation

Irrigation non-uniformity could be caused by the result of systematic non-optimal conditions and one-off conditions. On the one hand, a clogged or damaged nozzle, uneven topography and system design issues could cause differences in pressure, and unequal field and irrigation system application limits could be the cause of systematic non uniformity. On the other hand, windy conditions or one-off small fails could cause randomized unpredictable non-uniformity.

In order to simulate variable irrigation events, the following steps were identified: Firstly, irrigation non-uniformity had to be experimentally assessed. Then the variability in the applied depth and its probability of occurrence identified for the different irrigation systems. Finally that variability would be independently reproduced on each of the irrigation events.

In order to assess linear move and hosereel with boom system application uniformity, data from several in-field irrigation evaluations were used. Using these catch can data, a pattern that would allow the reproduction of irrigation non-uniformity in those systems could be generated. In 2011, 2012 and 2013, boom and linear move systems were evaluated on different fields in Elveden Estate, Norfolk, and on different dates (Appendix E for details on irrigation evaluation procedure and data collection).

From these irrigation evaluation datasets, the relative differences between the individual measurements and the average depth applied were estimated. The relative deviation of individual measurements was estimated as:

$$dev (\%) = \frac{x_i - \bar{x}}{\bar{x}} * 100 \quad \text{Equation 11}$$

Where x_i is the individual records, and \bar{x} the average value of that irrigation evaluation which coincided with the scheduled depth. Average deviation values for the linear move and boom irrigation systems are shown in Figure 19. This figure presents a histogram representing the average variability occurring under boom and linear move irrigation systems. Under linear move nearly 50% of the deviation falls into -5% to +5%, whilst application with the boom about one third

(33%) in this range. This suggests that the performance of the booms which were tested, was less uniform than the linear moves'.

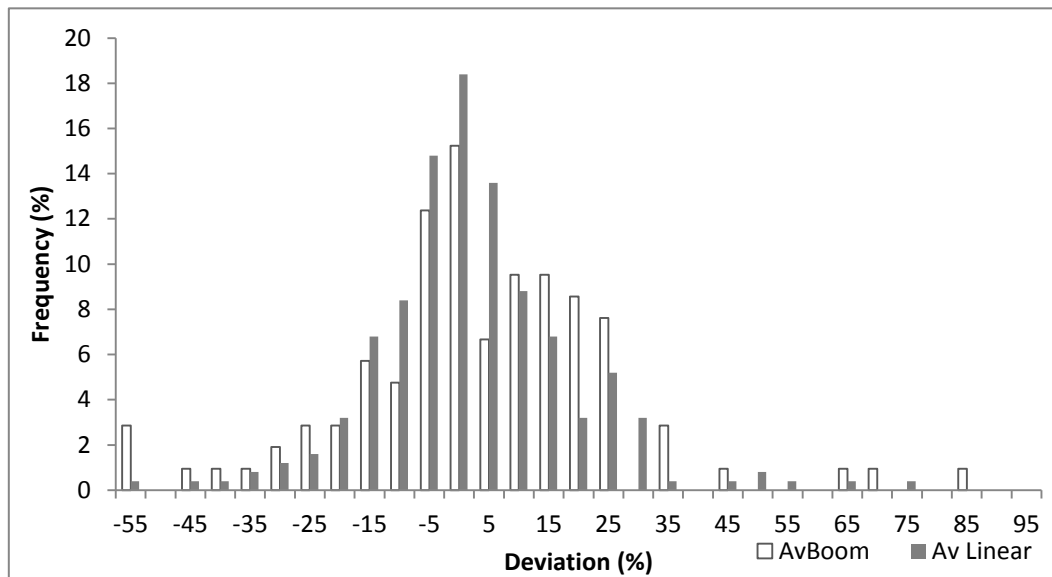


Figure 19 Histogram showing the average variability in irrigation deviation (%) occurring in boom and linear move irrigation application methods

In order to generate the irrigation files needed by AquaCrop, each of the *reference* irrigation events had to be randomly modified using previously obtained results containing irrigation system, deviation and frequency of occurrence.

At this stage, 2000 irrigation files (100 seasons, 5 different climatic conditions on two different soils) were required. Their generation involved the use of the statistical environment R (<http://www.r-project.org/>). A script was written to automatically produce AquaCrop compatible irrigation files (.IRR), combining the reference irrigation schedules with random variations for each irrigation event.

Box1: An example of how an irrigation application was randomly modified.

Firstly, a list of figures was generated; in this list each deviation value (bin arrays of 5%) was represented with the same frequency as for the given irrigation system. In order to do so, the frequency (in percentage) was multiplied by 500, the resulting value rounded up to a whole number, and the corresponding deviation value repeated that amount of times in the list. The following example explains the procedure in detail.

For the boom the probability (frequency) of getting 25% less water than the average is 14.29%. This means, 14.29 times out of 100, a spot in a field would get 25% less water than the corresponding scheduled amount. In order to reduce the error due to fractions, 14.29 was multiplied by 5, giving 71.45. This value would get rounded to 71, and the corresponding deviation figure (-25%) included 71 times in a list of deviation values.

This procedure was followed for each of the deviation values and for both systems, forming two lists of numbers, in which the probability of randomly picking a certain value of deviation would be the same as its previously estimated frequency of occurrence for that irrigation application system.

5.2.2 Assessing statistical differences between soils, years, and irrigation systems

Statistical analyses were conducted to assess whether the resulting differences in yield simulations under different climatic conditions, soils and irrigation systems were statistically significant. The first step consisted of identifying the type of distribution followed by the scenario simulations' results. If it were possible to meet the assumptions of a linear model (for instance: normally distributed residuals, and homogeneity of variance), then parametric methods such as analysis of variance (ANOVA) would be the appropriate method. However, if the data did not meet these assumptions, and it was not possible by transformation coerce the data into meeting these assumptions, non-parametric methods such as the Kruskal-Wallis test (Kuskal & Wallis, 1952) – the so-called 'non-parametric ANOVA' should be considered (Lindman, 1974; Conover, 1971).

5.3 Results and discussion

Uniform irrigation

According to the irrigation triggers and applied water depths presented in the previous section, the following irrigation programmes were established for a sandy and a light sandy loam for a 'wet', 'average wet', 'average', 'average dry', and 'dry years'. The resulting irrigation programme is shown in Table 15 which presents the yield obtained for the given climatic conditions and the total applied irrigation. Further weather data are included in Appendix F: Weather data.

It has to be noted that the results are given in terms of t of dry matter per ha (t DM ha⁻¹). To calculate the equivalent green yield, the yield (t DM ha⁻¹) has to be divided by onion DM content (13%). Onion DM content was determined by a simple analysis (Appendix C.3) and contrasted with Lavey & Ober (2011).

Table 15 Reference irrigation applications (amount and total depth) for the agroclimatic conditions 'very wet', 'average wet', 'average', 'average dry', and 'very dry' years, sandy and sandy loam soils, and the simulated onion production.

Agroclimatic condition	Soil	
	Sandy	Sandy loam
<u>Very wet</u>		
Total irrigation needs (mm)	90	105
Simulated Yield (t DM ha ⁻¹)	10.5	10.2
<u>Average wet</u>		
Total irrigation needs (mm)	96	110
Simulated Yield (t DM ha ⁻¹)	9.6	9.4
<u>Average</u>		
Total irrigation needs (mm)	164	150
Simulated Yield (t DM ha ⁻¹)	9.6	9.6
<u>Average dry</u>		
Total irrigation needs (mm)	198	265
Simulated Yield (t DM ha ⁻¹)	9.9	9.7
<u>Very dry</u>		
Total irrigation needs (mm)	286	360
Simulated Yield (t DM ha ⁻¹)	8.9	8.7

The resulting yield was considered to be the optimal baseline for onion production, representing a uniform irrigation application; this irrigation schedule was used as the basis for the generation of non-uniform applications.

As presented in Table 15 higher yields were obtained during the wetter season: 10.5 and 10.2 t DM ha⁻¹ (sandy and sandy loam soils) compared to 9.6 t DM ha⁻¹ for an average season on both soils, and 8.6 and 8.7 t DM ha⁻¹ under drier conditions. Irrigation increased for average conditions from 96 and 110 mm to 198 and 265 mm from the 'average wet' to the 'average dry' season, for sandy and sandy loam soil types.

Irrigation needs (IN) depend on the SWD, as explained in the methodology. In the modelled irrigation schedule, irrigation is based on a specific soil deficit which triggers a water application. Theoretically the IN for both soils under the same weather conditions should be very similar, however, as shown in Table 15 the estimated IN on the sandy loam were generally marginally higher.

Crop water requirements depend upon water evaporation from the soil and crop transpiration (ET_c). The quantity of evaporated water can be described by the Readily Evaporable Water ($REW=1000*(\theta_{FC}-\theta_{air\ dry})Z_{e,surf}$; Raes *et al.* 2011)) from the top soil layer. This is based on the difference between the volume of water at field capacity and in air dry soil, in the evaporating soil surface layer. Consequently, water evaporation from a soil with higher water retention properties would be greater, and therefore irrigation requirements are higher.

On the other hand, crop transpiration was greater on the sandy soil, especially towards the last stage of the crop cycle, when the canopy has developed fully. As a consequence of the higher transpiration, and because AquaCrop is a water driven model, higher biomass would be produced, and so a higher yield.

The simulated yield for the 'wettest' year was the highest; conversely, during the 'driest' year, the lowest yield was simulated. Onion production during the 'wettest' year would probably have a low quality. Rainfall was the highest through the season (500 mm). Due to low temperatures, crop maturity

(determined by accumulated GDD) was not reached until the 11th of October (Table 16). A yield of over 10 t of DM ha⁻¹ would correspond to a green yield of over 70 t ha⁻¹. However, due to a very wet September (160 mm) there would be problems reaching maturity, whilst farm machinery would encounter problems at harvest. Furthermore, quality issues would most likely develop due to the high moisture content (Corgan *et al.* 1990); wet bulbs can develop problems (mainly related to fungal diseases) during storage.

Table 16 Simulated maturity dates for 'very wet', 'average wet', 'average', 'average dry', and 'very dry' seasons.

Year	Maturity date
Very wet	11 th October
Average wet	13 th September
Average	12 th September
Average dry	11 th October
Very dry	19 th September

During the 'driest' year, seasonal (March to mid-September) rainfall (138 mm) and ETo (682 mm) resulted in irrigation needs (IN) of 286 mm and 360 mm for the sandy and sandy loam soils, respectively. IN is the difference between the crop water need (ETc) and that part of the rainfall which is effectively used by the plants (Pe) (Brouwer & Heibloem, 1986). This season could have been the most productive if the irrigation schedule had been able to match the crop water requirement.

Non-uniform irrigation

Each scenario, based on the different combination of soil and agro climatic conditions, was run 100 times using the variability occurring in a linear move, and 100 times using the variability of a boom irrigation system. The onion yield for the 2000 simulated seasons is shown in Figure 20 as a box and whisker plot. A box and whisker plot shows the median (central line, Q₂), upper quartile (top of the box, Q₃), lower quartile (bottom of the box, Q₁), plus the upper and

lower adjacent values (vertical lines above and below), which are the maximum and minimum values within 1.5 times the interquartile range of the upper or lower quartile. The interquartile range is the difference between the upper and the lower quartiles. Outliers, which are greater or smaller than the adjacent values are displayed as points.

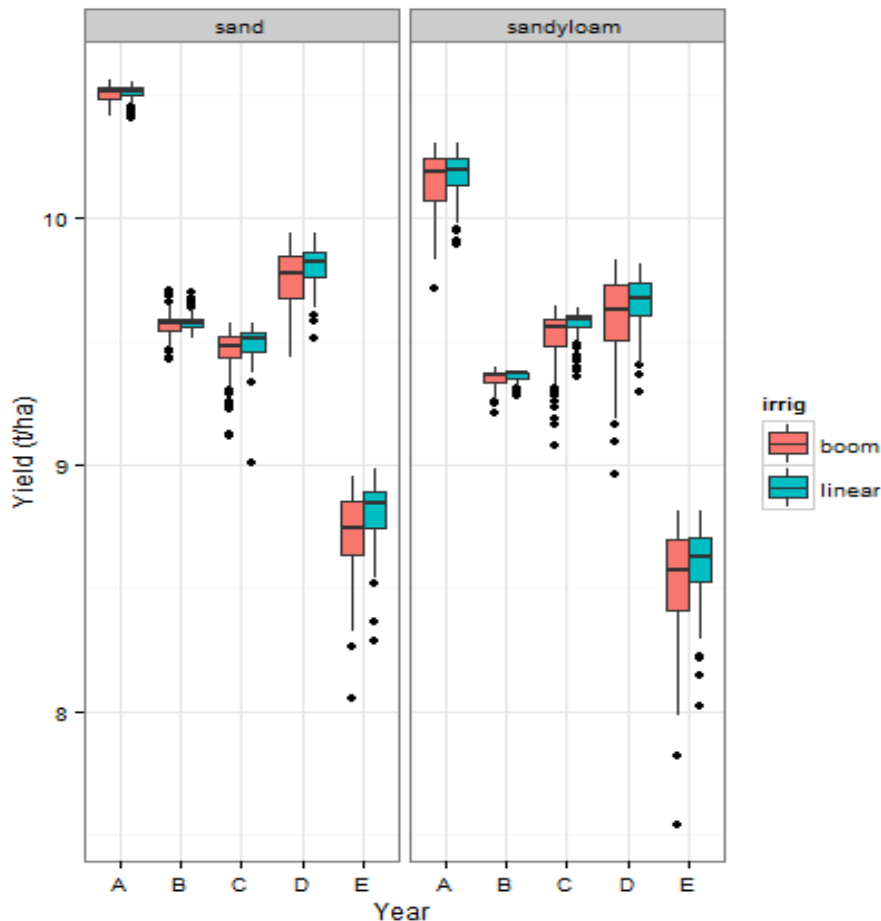


Figure 20 AquaCrop simulated onion yield ($t\ ha^{-1}$) for five contrasting years (A: very wet, B: average wet, C: average, D: average dry, and E: very dry) on two soil types (sand and sandy loam), under two different irrigation systems (a hose reel with boom and a linear move).

Figure 20 shows that the highest yield and lowest variability was obtained for the wettest climatic conditions. The lowest yield and the greatest variability

occurred in the driest year. On the sandy loam soil type, for the average years ('average wet', 'average' and 'average dry'), yield and its deviation increased for increasing agroclimatic dryness. However, on the sandy soil, yield during the average wet season was greater than for the average conditions.

The greatest variability in the results occurred for both soils under very dry agroclimatic conditions. During drier conditions, irrigation was supplied through very frequent applications (17 irrigation events on the sandy soil and 15 on sandy loam) compared to wetter conditions; the greater amount of application enhanced the effects of irrigation non-uniformity. In less arid conditions, when the irrigation is less frequent, rainfall compensates unequal irrigation applications.

Median yield obtained under boom application systems were lower than for systems with linear moves fitted to hoses, additionally resulting yield variability was greater. This confirms the effects on onion yield of the lower uniformity identified during the irrigation evaluations on the tested booms (shown in Figure 19).

In order to statistically determine the differences between the results in yield production of the scenarios observed in Figure 20, the following study was conducted. Normal distributions are very frequent continuous probabilistic distributions in nature (Everitt, 1998). They represent a symmetric data distribution around a mean (Figure 21).

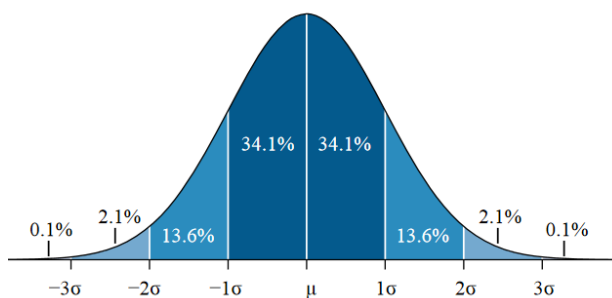


Figure 21 Schematic representation of a normal distribution around a mean μ , with a given standard deviation σ

However, the results of the non-uniform irrigation application do not follow this distribution. It can be appreciated looking at the location of the quartiles (box-and-whisker plots in Figure 20) that

most of the results for a given group (combination of soil x climatic condition x irrigation system) are concentrated in the upper section ($[Q_3-Q_2] > [Q_2-Q_1]$), presenting a longer tail towards the lower values. Additionally, a study of the residuals (difference between the observations and the group's mean) distribution corroborated the absence of a normal distribution (Section G.1 in Appendix G).

Non-normal distributions can be transformed into normal distributions applying mathematical conversions (Crawley 2007). Individual data would be transformed to then meet the assumption of normality (Everitt, 1998). Several transformations (natural logarithm and various powers) were tested, however it was not possible to obtain normally distributed residuals.

In addition to this non-normality, the dataset suffered from heterogeneous variance (Crawley 2007). It was observed that the driest years produced the lowest yield, but also the greatest variability, therefore a link exists between the magnitude of each group (soil x climatic condition x irrigation system) mean and the magnitude of each group variance. This link is usually investigated by plotting the residuals against the fitted values generated by a particular model. A diagnostic plot (Section G.1 in Appendix G) followed a classic wedge shape indicating heterogeneous variance (Crawley 2007).

As a result of these two issues, it was not possible to use parametric statistical techniques, ANOVA was therefore unsuitable.

Unlike ANOVA, the Kruskal-Wallis non-parametric analysis of variance does not assume normally distributed residuals, nor homogeneous variance. Like the Mann-Whitney test, the Kruskal-Wallis test works by ranking all the data values, across all groups, according to their size: the smallest value becomes 1, the second smallest 2, etc. This ranking results in a loss of power, though this problem can be avoided with a sufficiently large sample size. A test statistic is then computed, and from this a P-value can be approximated using the chi-squared distribution (Conover, 1971).

Kruskal-Wallis tests were completed with the R statistical environment, version 3.0.1, utilising the 'kruskal' function, implemented in the package 'agricolae' (de Mendiburu, 2010). Detailed results of this test are shown in section G.2 in Appendix G.

A summary of the results of the statistical analyses is shown in Table 17. This table shows the P-value for each of the factors and interactions. The letter in the column 'significance group' indicates whether the groups (soil, year, irrigation system or any of their interactions) are significantly different. Different letters represent statistical differences.

The factor (soil, irrigation and agroclimatic year) and their interactions (soil-year, and year-irrigation) were significant as well as the triple interaction ($P < 0.05$).

These results add statistical evidence to the interpretations of Figure 20. From Table 17 it can be seen that yield on sandy soils is on average statistically significantly higher than on sandy loam soil types. The highest yield was produced under the wettest conditions, followed by the average dry agroclimatic year, then by the average season, and average wet, lowest production being in the extreme dry. Simulated onion production was greater under non-uniform irrigation applied by the linear move system than by the boom.

The study of the combined effects on yield production of irrigation non-uniformity produced by the two irrigation systems and the agroclimatic conditions, showed no significant differences during the extreme seasons ('very wet' and 'very dry') nor during the 'average wet' year. However, during the 'average' and 'the average dry' seasons the differences in average yield were significant. In those cases yield produced under the irrigation non-uniformity of linear moves was on average 60 and 40 kg DM ha⁻¹ greater than under the boom non-uniformity.

The last part of the analysis considered all possible interactions. These results add some significant observations to those previously stated. It shows that during 'average dry' and 'average' agroclimatic conditions, both factors, soil

type and irrigation system, have an effect on onion yield production. For an 'average dry' year, highest yield would be produced on sandy soils, contrary under 'average' agroclimatic conditions. Onion production regardless of soil type would be higher under irrigation applied by linear move systems. Additionally, these results point out that during a 'very dry' season, yield would only be significantly different on sandy soils.

Table 17 Summary of Kruskal-Wallis analysis. Average yield and P-value for groups considering factors soil, year, and irrigation system and their interactions. Letters indicates whether the groups are significantly different.

Signific. Groups	Treatment / interaction	Mean (t DM ha ⁻¹)	Signific. groups	Treatment / interaction	Mean (t DM ha ⁻¹)
Factor: Soil (P value <0.001)			Year – irrig - soil (P value <0.001)		
A	sand	9.61	A	A:boom:sand	10.51
B	sandyloam	9.45	A	A:linear:sand	10.51
Factor: Year (P value <0.001)			B	A:linear:sandyloam	10.18
A	A	10.33	B	A:boom:sandyloam	10.15
B	D	9.70	C	D:linear:sand	9.81
C	C	9.51	D	D:boom:sand	9.75
D	B	9.47	E	D:linear:sandyloam	9.65
E	E	8.66	F	D:boom:sandyloam	9.60
Factor: Irrigation (P value=0.0341)			Fg	C:linear:sandyloam	9.58
A	linear	9.56	Fg	B:linear:sand	9.58
B	boom	9.52	G	B:boom:sand	9.57
Interac: Soil - year (P value <0.001)			H	C:boom:sandyloam	9.52
A	sand:A	10.51	i	C:linear:sand	9.49
B	sandyloam:A	10.16	j	C:boom:sand	9.46
C	sand:D	9.78	k	B:linear:sandyloam	9.36
D	sandyloam:D	9.63	k	B:boom:sandyloam	9.35
E	sand:B	9.58	l	E:linear:sand	8.80
F	sandyloam:C	9.55	m	E:boom:sand	8.73
G	sand:C	9.45	n	E:linear:sandyloam	8.59
H	sandyloam:B	9.36	n	E:boom:sandyloam	8.51
I	sand:E	8.78			
J	sandyloam:E	8.55			
Interac: Year – irrig (P value <0.001)					
A	A:linear	10.34			
A	A:boom	10.33			
B	D:linear	9.73			
C	D:boom	9.67			
D	C:linear	9.53			
E	C:boom	9.49			
Ef	B:linear	9.47			
F	B:boom	9.46			
G	E:boom	8.62			

The last part of the scenario analyses and interpretation, consists of comparing the effects of irrigation non-uniformity with the results of uniform irrigation

applications. Figure 22 presents the results of AquaCrop simulated onion yield under the chosen five agroclimatic conditions (A: very wet, B: average wet, C: average, D: average dry, and E: very dry) grown on two different soil types (sandy and sandy loam) under uniform and non-uniform irrigation applications.

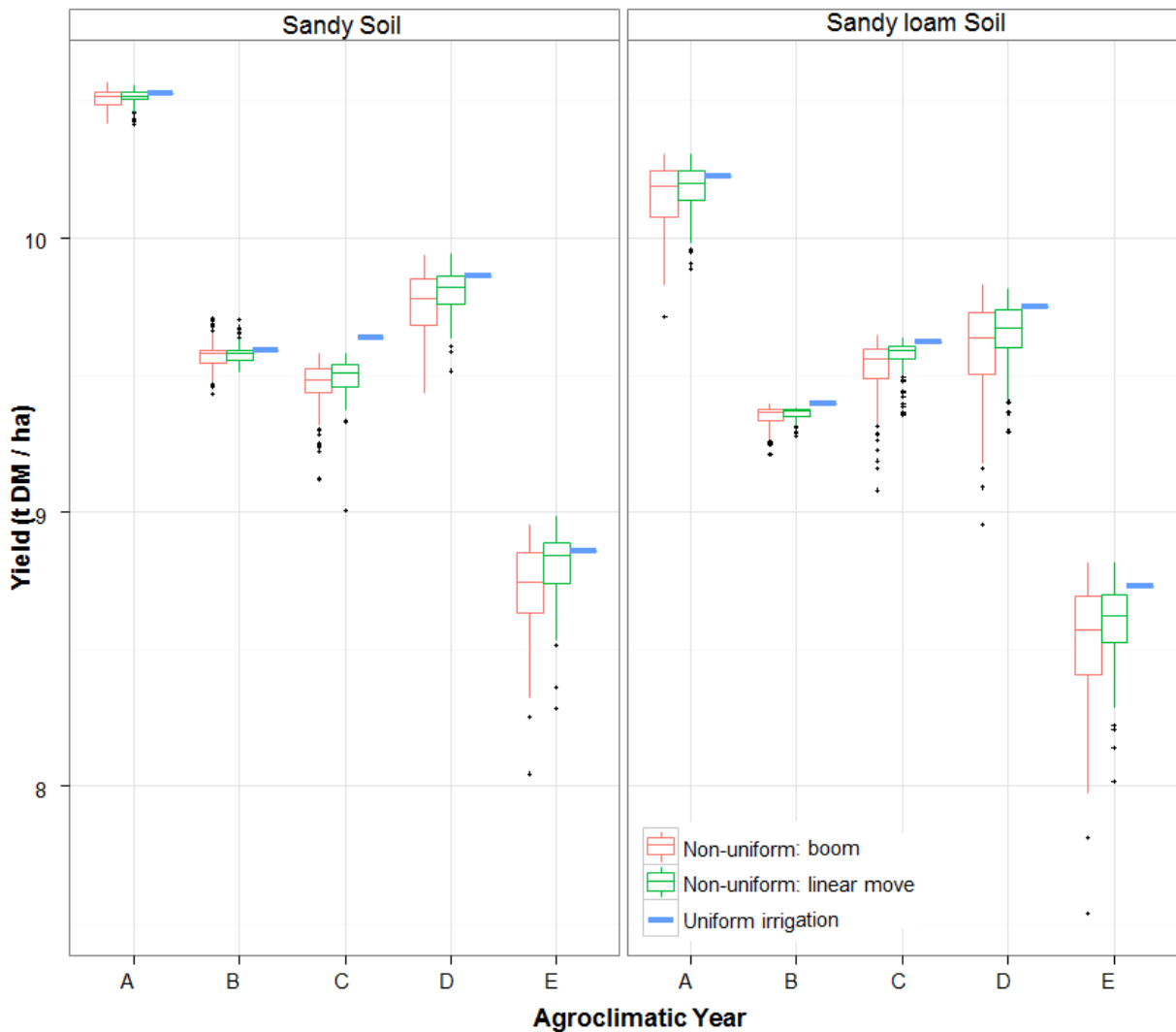


Figure 22 Simulated onion yield (t DM ha⁻¹) under uniform and non-uniform (boom and linear application systems) irrigation applications, on sandy and sandy loam soil types, for different agroclimatic conditions (A: very wet, B: average wet, C: average, D: average dry, and E: very dry).

It can be appreciated that onion yield under uniform irrigation is generally higher than under non-uniform applications. Uniform applications produce yield that is

above the median (Q_2) and in some cases also the higher quartile. This means that between 50 and 75% of the results of non-uniform irrigation simulations are below the yield produced in case of uniform applications. These differences are greater for the drier years and in cases of boom application systems.

Resulting simulated yield variability could be interpreted as the component in the overall yield variability obtained by growers, which is exclusively caused by variation in irrigation inputs.

Figure 22 explains the previously indicated non-normality in the distribution of the simulations' results. There is a potential yield value (close to the yield under uniform irrigation) from which production changes (mostly negatively) under non-uniform conditions.

Under irrigated conditions with no limitations in water usage, the highest yields would have been expected to occur during the driest conditions. However these are generally also the seasons with the highest temperatures. As shown in Figure 22, greatest simulated yield was registered under the wettest conditions.

In the years qualified as wet and very wet following the PSMD ranking, the rainfall and ETo totals were broadly similar, unlike the dry conditions when ETo was greater, especially in summer months. However, during the drier years, slightly lower average temperatures were registered during from April to August (average of 2°C difference). The lower temperatures at the beginning of the production season and during maximum canopy growth limited the development of the canopy cover, and consequently total biomass and yield.

The method used to choose climatic conditions to run the model confounded other factors that could have affected onion yield production. The results have been treated equally regardless the location of the weather station. Buxton weather station, used for the extreme wet year, for instance, is located 15 km away from the North Sea coast and the rest of the stations are inland. The latitude of the chosen weather stations ranges from 52.75°N to 52.00°N. This

difference in latitude could have consequences on the crop development that have not been taken into account.

In order to study the effects of irrigation variability, seasonal difference between the scheduled irrigation depths and the simulated applications were estimated and plotted against yield variation. The difference was calculated as shown in Equation 12, and irrigation variability as presented in Equation 13.

$$Diff = |simulated\ applied\ depth - scheduled\ depth| \quad \text{Equation 12}$$

$$var = yield_i - yield \quad \text{Equation 13}$$

The effects on yield were estimated for each combination of soil, irrigation and year, as the difference between simulated ($yield_i$) and average values (\overline{yield}) for each combination soil*year*irrigation. The results are shown in

Figure 23 Simulated yield variation respect to the average (t/ha) for each combination soil*year*irrigation depending on the seasonal difference between scheduled and applied irrigation (mm)

. For the wetter years, yield variation is generally smaller (less than $0,25\ t\ ha^{-1}$) and the difference between scheduled and simulated irrigation application is less than 25 mm. However the yield difference is greater under drier weather conditions. It can be observed that the difference in applied water depth increased up to 25 mm, 50 mm and 75 mm for average, dry and very dry years, thus leading to decrease in yield. The drier the conditions, the more negative the yield response becomes.

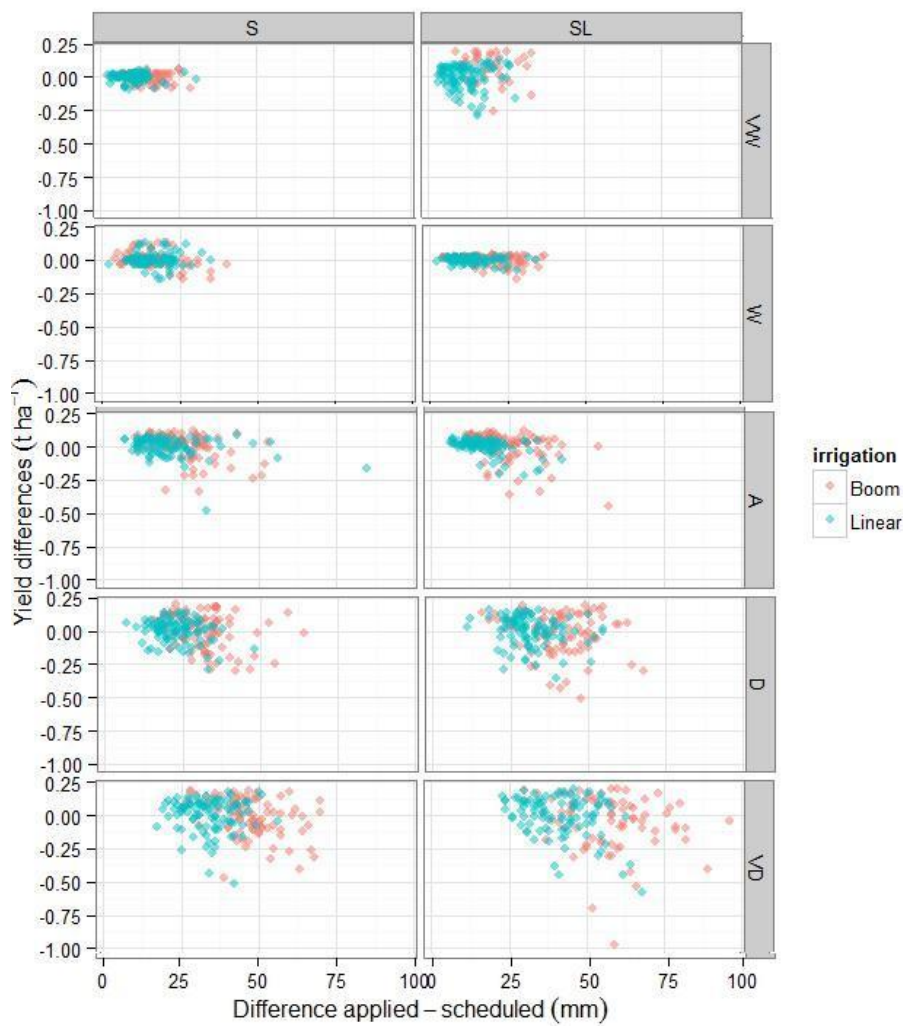


Figure 23 Simulated yield variation respect to the average (t/ha) for each combination soil*year*irrigation depending on the seasonal difference between scheduled and applied irrigation (mm)

The yield produced under uniform irrigation is the potential yield growers could achieve in case of implementing their irrigation systems. Further discussion of the implications of the modelling, including methodological limitations and contributions to knowledge for the industry and science communities are given in Chapter 6.

Chapter 6. Discussion and implications of research

This chapter describes the implications of the research for science and industry, the methodological limitations, recommendations for growers and areas for future research.

6.1 Implications for science and research

The original contribution to knowledge arising from this research includes the validation and calibration of the FAO AquaCrop model for onions in the UK. AquaCrop has previously been validated and used to assess irrigation practices in other crops such as wheat in Iran (Andarzian *et al.* 2011; Salemi *et al.* 2011), paddy rice in China (Lin *et al.* 2012), maize in Pennsylvania (Mebane *et al.* 2013) and teff (*Eragrostis tef*) in Ethiopia (Araya *et al.* 2010), but has not been used for assessing crop yields of onion grown under supplemental irrigation conditions in a humid climate in the UK.

This research set out to understand and assess the links between soil and irrigation variability on UK onion production. Onion yield variability is the response of a combination of environmental, genotypic, and agronomic factors (Marino *et al.* 2013). Previous studies revealed that variance in yield could be influenced by factors such as genetic potential, fertilisation rates (M. Islam *et al.* 2007), and soil characteristics (electric conductivity, pH, or available nutrients, (Darwish & El-Kader 2008)). However, there is very limited published research on the impacts of irrigation heterogeneity on onion yield. This research aims to address that gap and provide new modelled information to inform developments in precision irrigation.

Scenario modelling to assess different non-uniform irrigation applications under different soil and agroclimatic conditions identified the effects of irrigation application heterogeneity on onion yield. The modelled outputs showed that for drier conditions, irrigation variation could generate variations in yield of up to 0,5 t ha⁻¹. Effects were greater on sandy loam soils. Under wetter conditions, the differences in water applications on yield were compensated for by buffering

effects of rainfall. For drier conditions, seasonal difference between simulated and scheduled water applications were greater and consequently yield variation greater.

The growers interviewed as part of the industry survey identified seasonal in-field and field to field yield variability of c30% (in-field) to c40% (field to field) (Chapter 3). That is the reported response of onion yield production to factors (soil, irrigation, fertilization, and other characteristics) that vary across and within fields. Onion yield variability obtained through scenario modelling represents the variability occurring on a homogeneous soil due to non-uniform irrigation, explaining part of that variability as the result of a single factor.

Final yield and irrigation needs were estimated for two different soil types. Irrigation needs were generally higher on sandy loam soils. However, the yield was greater on sandy soils. In the case of soils, no in-field heterogeneity in soil type was considered.

Inman-Bamber *et al.* (2005) have highlighted the advantages in using crop growth models for research. Firstly, the response of certain systems to a series of management and environmental factors can be predicted. Crop models are of great value in reproducing certain conditions for which field trials would be too expensive, and for studying long-term effects. They also stated that models are especially powerful for studying temporal and spatial variabilities in soil characteristics and agroclimate.

In this study, considering the implementation of precision farming, modelling allows the assessment of several factors which have potential effects on onion cropping, yield and quality. Costs and time of conducting experimental trials are saved using a crop modelling approach. This thesis focussed on the effects of water and climate variability on yield; however, other parameters such as soil spatial variability, irrigation schedule, management practices could also be studied.

Finally, it has to be noted that the concept of onion 'quality' has different meanings. Some areas of research focus on the pharmaceutical and organoleptic features, such as pungency (Yoo *et al.* 2006; Enciso *et al.* 2009; Rodríguez-Galdón *et al.* 2008) or total soluble solids (TSS) (Kumar *et al.* 2007; Resemann *et al.* 2004). Other studies have investigated storability, development of certain components in storage (Chope *et al.* 2006; Abayomi & Terry 2009; Adam *et al.* 2000; Napier & Will 2011) and the effects of certain substances such as ABA on storability (Chope *et al.* 2007). The processing industry is interested in characteristics such as scale thickness (Yutaka & Makoto 1997) as it determines drying time, and in obtaining 'single-centre bulbs' (Pelter *et al.* 2004). Most growers, as discussed in Chapter 3, aim to produce a disease-free crop composed of bulbs that are homogeneous in size, shape, skin finish and colour. This highlights the importance of identifying the quality aspects of interest in onion research.

6.2 Implications for the industry

This thesis includes the parameters used to calibrate and validate the AquaCrop model to simulate onion yield response. These models are powerful tools from which growers and the wider industry can gain significant benefit. For example, they can assist in decision-making processes such as scheduling irrigation, or choosing from a variety of crops under certain conditions or restrictions (e.g. extreme weather conditions, water restrictions, energy or water price increases). Such models can also be used to forecast yield production and make decisions about storage time and capacity. Options should therefore be investigated to maximise the benefits and application of this crop model for other uses in the industry.

For UK onion growers the results of the scenario simulation shows that irrigation performance has a key impact on onion yield and variability. This highlights the importance of irrigation uniformity under different application systems. For those growers who identified a great variability between fields or within a single field, it

will be useful to know that such variability may be caused by their irrigation system; this is particularly relevant to growers who irrigate solely with rainguns.

For the irrigation industry, the ability to simulate and assess the effects of improvements in irrigation application equipment, management and other technical implementations (e.g. variable rate application) could help to engage growers in the uptake of new technologies.

6.3 Methodological limitations

This section presents some of the key limitations in the methodology and approaches developed, with special attention to the crop modelling process.

For model parameterisation, most of the parameters were found in the existing literature. However, for others that were not available, these had to be chosen from a range of values or from experiments. Parameterisation was therefore sensitive to the source and provenance (quality) of the data.

For the crop modelling process (calibration, validation and scenario modelling) no 'set' planting was considered, only drilling. Fertilisation was also considered to be optimal; accordingly, no limiting effects of nutrient stress were considered. The AquaCrop model does not simulate pests or weeds; therefore the simulated crop consisted of a perfectly fertilised, pest and weed free crop.

Onion bulb initiation is determined by multiple factors including photoperiod (J L Brewster et al. 1977; Lancaster et al. 1996). The AquaCrop model, as a water balance driven model, does not include the influence of day light duration or light intensity. This limits its accuracy for initiation prediction.

Certain assumptions were made to simplify the modelling process. Regardless of climatic conditions, the planting date each year was fixed (1st March). In practice, the planting date would vary according to soil and atmosphere temperature, and the soil moisture content and weather forecast.

The simulation of irrigation non-uniformity did not consider the whole spectrum of irrigation non-uniformity. The simulated deviation was possibly due to wind,

occasional blockage, or temporary variations in pressure. In order to undertake a more complete study, systematic non-uniformity should also be considered.

The calibration of the model generally showed good performance; however, in cases of extreme water withdrawal, the simulated crop response was very poor. The model is therefore not accurate under these modelled conditions, and should not be implemented assessing impacts of extreme water deficit conditions on crop yield without additional parameterisation. It would be of great use for research purposes and commercial onion growers, that further studies would consider calibrating AquaCrop for onions grown under extreme dry conditions.

In this study, the AquaCrop model has been shown to perform well when simulating crop yield response to water inputs for onions, and has been successfully used for other crops in other studies (Araya *et al.* 2010; Andarzian *et al.* 2011; Salemi *et al.* 2011). However, it does not give a direct estimate of crop quality. For onions, the probability of getting fungal disease, regrowth, or lack of maturity due to wet conditions at the end of the season can be interpreted by using soil moisture, crop stage development, and time of maturity. Other quality parameters such as bulb size distribution are also not predicted by the model. These results could be estimated combining simulated final yield with planting density such as the work by de Visser & van den Berg (1998) in their physiology based onion growth model ALCEPAS (C L M de Visser 1994).

Another very important issue is that the experimental part was conducted by an external research body. If those experiments and measurements were to be repeated, dry matter content through the whole crop cycle and at harvest could be determined so as to provide a better indication of biomass. It would also be useful to precisely monitor crop development, identifying specific crop stages and duration. Knowing accurately the date of emergence and bulb initiation would be valuable in establishing crop phases more accurately.

The industry survey was planned at an early stage of the research process and was very useful to generate a great picture of the onion industry. However, it would have been of enormous value to record detailed data for typical and extreme cropping years. Addressing questions relating to specific irrigation application rates, total annual applied depths, and data on detailed extension under different cultivation/irrigation methods would also have been particularly useful.

6.4 Recommendations for growers

Nowadays, as confirmed by the growers interviewed, most conduct a detailed monitoring of their fields in terms of climate, management practices (irrigation, fertilisation application, planting dates/density, etc.) and yield production. The wide range of recorded data could be used to explore their individual potential. Studies of specific sites and conditions, combined with economic assessment could be combined to help in taken decisions. This would involve the acquisition and understanding of crop growth models and the later scenario modelling. Currently this is getting easier and most of the resources and information are free to use. Growers could and should benefit from these tools.

Through modelling, it has been identified the importance of irrigation non-uniformity on onion yield production. It is on the growers' hands to identify the source of the variability in their production and minimize their effects. For instance, applying irrigation to meet the specific requirements of individual plants or managing units and minimize adverse environmental impacts (Misra *et al.* 2005; Raine *et al.* 2007) would increase farmers' water and economic efficiencies. Matching irrigation inputs to yield in each area of a field could help reduce costs of production.

Irrigation has the potential to be a precision activity involving the accurate assessment of the crop water requirements and the precise application of that volume at the required time. Water requirements would defer according to special variability in topography, soil type, soil water availability, landscape features, and cropping systems (K. C. Stone *et al.* 2006).

6.5 Future research

Model implementation

AquaCrop has shown a good performance of average climate and irrigation conditions. However, for the extreme cases of water deficit its predictions were very poor. Future work on the modelling site should establish the effects of extreme water deficit on the simulated crop development, and biomass and yield production.

Factors affecting onion yield production

This thesis has identified irrigation as one of the components explaining onion yield variability. However, there are other effects that still need to be identified and quantified. Soils (texture, nutrient availability, pH, salinity) are a potential source of variability in onion yield production. Future work should study the effects of soil features on onion production. Of special interest, as pointed by most of the interview growers, is the presence of CaCO_3 (chalk) and its effects on soil temperature and consequently crop maturation.

Economic assessment

Cases of irrigation non-uniformity have been contrasted against uniform (*reference*) irrigation applications. An economic assessment considering the costs of implementing application equipment and the benefits of reducing irrigation variability or implementing towards precision irrigation should help assessing its economic viability. This study should take into account climatic uncertainty and consequences of climate change.

6.6 Challenges facing future UK onion production

In the coming years, growers will be facing new challenges, being the most immediate the need to satisfy year-round supply. Supplying the market year round means earliness of harvest and the need of storing bulbs long enough. According to the interviewed growers, perceived price needs to be high enough to compensate the extra costs and risks of an early harvest and the investment

in long storing facilities and energy. UK growers will also have to encounter external concurrence, especially from Dutch bulbs.

Furthermore, in the coming years the use of some chemicals will be restricted, and growers will have to face new approaches to fight against disease pressure. Water supply may also become an issue: reduction in water abstraction licensing, or temporal limited availability. This would become a serious issue, as most of the growers rely on irrigation to ensure a quality production. Breeders will continue fronting the challenge of onions producing homogeneously sized bulbs. Growers' main concerns in onion production are water, fungal and bacterial diseases, fertilisers, soils and pests in this order. Therefore pressure on water sources and agro-chemicals restrictions represent an increasing concern.

In addition to these, agronomists believe onion growing will become more cost effective and production will be more economically profitable. Increasing marketable yield and reduction in inputs is the major challenge. Additionally, integrated approaches should be acquired across all elements of the growing in the large commercial scale. These include water timing, nutrition, crop rotation, and timing options.

Chapter 7: Conclusions

This thesis aimed to assess the impacts of irrigation variability on onion crop yield. A summary of the main conclusions with respect to the objectives defined in Section 1.2 is presented below:

Objective 1: To review and assess the scientific evidence on the relationships between onion yield, crop water use, irrigation and crop quality

A detailed scientific and grey literature review was completed. The review of onion productivity and water use relations highlighted a number of salient issues. Onion is particularly sensitive to water deficits during emergence and transplant, and to both deficit and water excess during the rapid bulb growth periods. Water restrictions during crop growth (total water withholding and controlled deficit irrigation) resulted in lower yields and smaller bulbs. Early bulb maturity was identified as a result of growing the crop under water stress, causing secondary problems including early rotting in storage. Several studies have determined onion K_c values and reported on contrasting values (0.4-0.7 / 0.85-1.05 / 0.6-0.75) depending on climate and location. An attempt to minimize these differences was reported by correlating K_c to GDD. Total irrigation requirements are reported to range between 225 and 1040 mm to yield between 10 and 77 t ha⁻¹, leading to WUE and IWUE of 34 to 102 and 46 to 281 kg ha⁻¹ mm⁻¹, respectively. Irrigation and water efficiency is thus highly influenced by agroclimate, the method of irrigation application and final yield.

Quality is also a key constituent of modern onion production. The most important limiting factors in storage are sprout growth and bacterial and fungal diseases, with the latter being strongly correlated to prolonged wet periods. Internationally, current trends show a move away from traditional surface (furrow) irrigation to more advanced and efficient micro (drip) and overhead (sprinkler) systems capable of applying water with greater precision and timing. Finally, the drivers of change identified from the literature and an industry

survey of grower practices included the need for greater product traceability, quality assurance and managing the rising costs of energy.

Objective 2: To parameterize, calibrate and validate a suitable bio-physical model.

The literature was reviewed to find the most suitable crop model based on a set of criteria described in Chapter 4. FAO AquaCrop model was chosen as the most suitable crop growth model for this research's purposes.

The scientific evidence in the literature (Chapter 2) and results from the UK onion industry survey (Chapter 3) were combined and used to inform this process. The AquaCrop model was then calibrated and validated for brown onion (*cv Arthur*) cultivation in the UK using experimental data from a series of irrigation trials on onions during 2010-2012. Statistical analysis was used to assess model goodness of fit. Following model validation, the AquaCrop model was used to study different scenarios assuming uniform and non-uniform irrigation impacts on onion yield.

Objective 3: To simulate the impacts of soil and water variability on onion crop yield using a stochastic modelling approach.

A series of scenarios were defined based on UK growing areas, typical and extreme weather and general onion cropping practices. Uniform and non-uniform irrigation applications were simulated and its effect on onion yield production assessed under a series of 5 climatic conditions and 2 different soil types.

AquaCrop onion yield simulations showed lowest yield production and greatest variability for the driest agroclimatic conditions. Additionally, simulated yield on sandy soils has greater than on sandy loam soils, concluding that sandy soils would result more productive. Hosereels fitted with booms supplying irrigation would produce in average lower onion yield, compared to systems fitted with linear moves.

During extremely wet and dry seasons, as well as for average wet years, the differences in yield under the studied non-uniform irrigation systems were not significant. However, for 'average dry' and 'average' conditions, the effects of different soil types and irrigation applications systems had significant consequences on yield production. Under 'average dry' conditions, the highest yield would be produced on sandy soils, however, during 'average' agroclimatic conditions the highest production would be on sandy loam. On both soil types onion production was higher under irrigation applied by linear move system. For 'very dry' seasons, the effects on yield between the considered water application systems would only be of significance on sandy soils.

The study of uniform vs. non-uniform irrigation applications predicted that produced onion yield is higher under uniform irrigation. Those differences increased with increasing dryness. Differences were greater in cases of boom application systems.

Objective 4: To develop recommendations for improving irrigated onion production on-farm to minimise the impacts of in-field soil and irrigation variability on crop yield.

Simulated yield variability from non-uniform irrigation applications could be understood as the isolated component of onion yield production variability triggered by crop water inputs. Growers attaining to implement irrigation application uniformity could find reductions on their production variability.

Future research should focus on encouraging better integration of our detailed biophysical understanding of onion crop agronomy with new developments in soil and water management. Further studies should assess other environmental and management factors affecting variability on onion production. Furthermore, the economic evaluation of implementation costs should be considered and contrasted to the potential benefits of yield variability reduction through new technology and techniques integration, such as precision farming.

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APPENDICES

Appendix A : UK onion survey: Questionnaires

A.1 Questionnaire 1: Questionnaire targeting GROWERS

Date:

Farm address:

Company:

Person interviewed / Job role:

1. General aspects

Total farm cropped area (ha)

Area dedicated to onions (ha) in 2012?

Typical size of onion fields (ha)

Do you keep records of

- Daily Rainfall (Y/N)
- Daily min and max Temperature (Y/N)
- Evapotranspiration (Y/N)
- Wind speed (Y/N)

If not, where do you get weather data from?

2. Production target and definition of quality

Which market do you target? Supermarket/Processing/Open Market

What are your customer's targets? Rank according to importance: High yield / Early or late production / Specific size / Disease free / Homogeneous size / Colour / Storability / Other

What is a high quality production for you? Rank according to importance: Size / Size distribution / Skin colour / Disease free / Intact skin / Colour / Storability / Other

3. Varieties

Do you drill or plant the onions? If both % of each: Sets (%) / Seeds (%)

Which growing cycle do you usually choose? Winter (%) / Spring (%)

Most commonly grown varieties on the farm and approx. % of land use:

- Brown: Armstrong, Arthur, Bennito, Centro, Hybelle, Hybing, Hybound, Hylander, Hytech, Jagro, Napoleon, Santero, Sturon, Tangito, Vision, Wellington
- Red: Electric, Red Baron, Red Emperor, Red Queen, Red Tide, Reddawn, Redspark, Renato

Are there different requirements in the varieties you grow in terms of...

- soil type (Y / N)
- water (Y / N)
- soil temperature (Y / N)
- Light requirements (Y / N)

Is onion variety selection linked to soil type? If yes, then why?

What is the seasonal variety selection base on...? Rank the following: Market demand / Quality / Price / Productivity / Suitable for local weather / Soil / Resistance to old/new diseases / drought tolerant / More responsive to water application / Contract / Storability

4. Soils

What are the typical soil types for the fields in which onions are grown on the farm?

Which are the best soils?

Which soil parameters can affect most your yield? Rank the following Soil clay content / Soil sand content / Low/high OM content / Slope / Waterlogging / Soil acidity/alkalinity / Shallowness /soil depth / Compaction / Crusting / Stoniness / Restrictive soil horizon / Others:

Which soil parameters affect the quality? Soil clay content / Soil sand content / Low/high OM content / Slope / Waterlogging / Soil acidity/alkalinity / Shallowness / soil depth / Compaction Crusting / Stoniness / Restrictive soil horizon / Others

In the fields where onions are drilled/planted, can you see difference in the following parameters? If yes, does that affect yield and/or quality?

- Soil type? (Y / N). If yes: Yield? (Y / N) ; Quality? (Y / N)
- Clay content (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Sand content (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Acidity? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Water retention? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Slopes? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Soil depth? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Other

5. Irrigation

Do you irrigate onion fields? Yes, all our fields / Yes, but only some fields / No

What application methods do you generally use on your onion fields? Hosereel fitted with raingun / Hosereel fitted with boom / Sprinklers / Centre pivot / Drip or trickle

What do you try to achieve through irrigation? -Assist establishment/germination / Reduce water stress effects on yield / Boost yield / Improve quality / Ease of harvest / Complement application of chemicals / Other

Do you schedule irrigation? Y / N

If yes, then what method/s do you use? In-situ soil moisture measurement / Water balance models / Combination / Walking the crop / Regular digging

Do you do it yourself or through an external consultant? On-farm / External consultant

What proportion of the onion crop is scheduled?

Do you define specific crop periods where you irrigate? Y / N

If yes, what is the trigger deficit on each soil type and volume applied at each stage?

What are the critical growth stages for irrigating onions?

6. Fertilisers

Do you follow Defra RB209 recommendations for P, K, and Mg?

Total amount of N applied per ha?

How does soil type impact on fertiliser management practices?

Do you keep records of fertilisation by field?

- Application dates (Y / N)
- Doses (Y / N)
- Source (Y / N)

Do you soil-map your fields in terms of nutrient concentration in the soil? Y / N

7. Yield

What is your average green yield in t/ha of...

- Brown: from sets / from seeds
- Red: from sets / from seeds

How much would you say (in %) that yield varies from...?

- field to field:
- Within a field, in a typical year
- year to year

Does size distribution matter?

Which size do you aim to get?

Which water related factors could reduce yield?

Which water related factors affect size distribution?

High yield vs. size distribution. What do you prefer? High yield / size distribution

What is the maximum possible yield given the conditions at your farm?

- Brown onions
- Red onions:

In a typical field of onions, what is the typical split in different sizes you want to achieve, and how does that usually vary in practice?

- Target: % 40-60mm / % 60-80mm / % +80mm
- Actual: % 40-60mm / % 60-80mm / % +80mm

8. Post Harvest / Quality

Which are the desired standards at harvest to maximise storability and post-harvest quality?
Prioritise the following: Disease free / Earliness of harvest / Lack of damage at harvest / Moisture content / Bulb maturity / other

Are there any effects of irrigation on post-harvest quality?

Are there any effects of soils on storability?

How does price vary with quality?

In case there is still some time of the meeting left and both parties accept to continue, the following questions will be asked:

Cultivation practices and crop development

What is the initial plant density for brown seeds / brown sets / red seeds / red sets?

What is the targeted plant density

What is the beds' width?

Does it affect yield?

What are the targeted planting dates for sets and seeds?

What are the desired conditions for planting/drilling? Rank them according to importance
Soil Temperature / Soil Moisture / Air temperature / Weather forecast Soil tillth

Which development stages and approx. duration do you distinguish?

Does water affect bulbing? How?

Does water affect the time when maturity is reached? How?

What is the typical length of the growing cycle in days?

- For onions grown from seeds
- From sets

What is the harvest's trigger in % of fall-over?

What are the main factors that have changed over the last 10 years in terms of irrigation management on onions?

What are the important future challenges facing UK onion production

Soils

Which soils on your farm would you avoid for onion cropping? Why?

We talked about in-field differences in terms of soil texture, slope, soil profile, etc. Do you try to minimize the effects of those differences on the crop? How?

Which other crops do you irrigate?

In case of having water restrictions, would you choose irrigating onions over the other crops?

Do you have any evidence of irrigation impact on onion yield?

Do you have data on rainfed and irrigated yields for the same year?

Do you keep records of...?

- Irrigation date (Y / N)
- Applied volume (Y / N)

Varieties

Have varieties changed over the years?

Which varieties do you think are the most difficult to grow on your farm?

Yield

Could you rank the following words according to the importance of their effects on yield? water – fertilisers – insects – fungal and bacterial diseases – soil

How does price vary with size?

Post Harvest / Quality

Could you link penalties in quality with:

- Irrigation scheduling
- Irrigation timing

General aspects

For how many years have you been growing onions?

Does annual onion cropped area vary annually? If yes how much?

If yes, then what are the main factors that affect the cropped area? Last year's production / diseases / Weather conditions / market requirements / Seed / sets price / yield price / Other

What is the typical crop rotation in which onions are included?

A.2 Questionnaire 2: Questionnaire targeting AGRONOMISTS

Date:

Location:

Company

Person interviewed: Job role:

1. General aspects

Where are onions mostly grown in the UK? (see and mark map)



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Typical size of onion fields (ha)

2. Production target and definition of quality

What is the relative weight of each of the following options in the supply to the final consumer?
Supermarkets / Processing industry / Open markets

What are the desired characteristics to supply

- Supermarkets: High yield / continuity / Specific size / Disease free / Homogeneous size / Colour / Price / Shape / skin finish / Storability / Other
- Open markets: High yield / continuity / Specific size / Disease free / Homogeneous size / Colour / Price / Shape / skin finish / Storability / Other
- Processing industry: High yield / continuity / Specific size / Disease free / Homogeneous size / Colour / Price / Shape / skin finish / Storability / Other

3. Varieties

Most commonly grown varieties on the farm and approx. % of land use:

- Brown: Armstrong, Arthur, Bennito, Centro, Hybelle, Hybing, Hybound, Hylander, Hytech, Jagro, Napoleon, Santero, Sturon, Tangito, Vision, Wellington
- Red: Electric, Red Baron, Red Emperor, Red Queen, Red Tide, Reddawn, Redspark, Renato

What do you base your recommendations on...? Market demand (Quality / Price) / Productivity / Suitable for local weather / Soil / Resistance to old/new diseases / Drought tolerant / More responsive to water application / Contract / Storability / Other factors

Is onion variety selection linked to soil type? If yes, then why?

4. Soils

What is the range of soil types on which onions are cropped across ...?

- this region
- the UK?

Which are the best soils? Why?

Which soil parameters affect yield the most? Could you rank them? Soil clay content / Soil sand content / Low/high OM content / Slope / Waterlogging Soil acidity/alkalinity / Shallowness /soil depth / Compaction / Crusting / Stoniness / Restrictive soil horizon / Others:

Which soil parameters constrain quality? Could you rank them? Soil clay content / Soil sand content / Low/high OM content / Slope / Waterlogging Soil acidity/alkalinity / Shallowness /soil depth / Compaction / Crusting / Stoniness / Restrictive soil horizon / Others:

In the fields where onions are drilled/planted, can you see difference in the following parameters? If yes, does that affect yield and/or quality?

- Soil type? (Y / N). If yes: Yield? (Y / N) ; Quality? (Y / N)
- Clay content (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Sand content (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Acidity? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Water retention? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Slopes? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)

- Soil depth? (Y / N) If yes: Yield? (Y / N) ; Quality? (Y / N)
- Other

5. Irrigation

Do growers usually irrigate onion fields? Yes, all of them / Yes, but only some / No

What application methods do they generally use? Hosereel fitted with raingun / Hosereel fitted with boom / Centre pivot linear / Drip or trickle

What is the objective of irrigation? Assist establishment / germination / Reduce water stress effects on yield / Boost yield / Improve quality / Ease of harvest / Complement application of chemicals / Other

Do they usually schedule irrigation? (Y/N)

If yes, which are the most popular irrigation method/s on onion fields? In-situ soil moisture measurement/ Water balance models / Combination / Walking the crop and digging the soil /

Would they do it themselves or through an external consultant? On-farm / External consultant

Is it important to define crop periods to schedule irrigation? (Y / N)

If yes, what is the recommended trigger deficit and depth applied at each stage?

What are the critical growth stages for irrigating onions?

6. Fertilisation

Do usually growers follow the RB 209?

Total amount of N applied per ha?

How does soil type impact on fertiliser management practices?

Do growers usually record fertilisation...

- Application dates (Y / N)
- Doses (Y / N)
- Source (Y / N)

7. Yield

What is your average green yield in t/ha of...

- Brown: from sets / from seeds
- Red: from sets / from seeds

Which are the most and the less productive varieties?

- Brown
- Red

How much would you say (in %) that yield varies from...?

- field to field:
- Within a field, in a typical year

- year to year

High yield vs. size distribution: What do growers usually choose? High yield / size distribution

What is the maximum yield growers in this region can get?

- Brown onions
- Red onions

In a typical field of onions, what is the typical split in different sizes desirable to achieve, and how does that usually vary in practice?

- Target: % 40-60mm / % 60-80mm / % +80mm
- Actual: % 40-60mm / % 60-80mm / % +80mm

8. Post Harvest / Quality

Which are the desired standards at harvest to maximise storability and post-harvest quality?

Are there any effects of soils on post-harvest quality?

Are there any effects of irrigation on post-harvest quality?

Does price vary with quality? How?

The following questions were kept to be asked in case of being time left in the meeting.

General aspects

Does annual onion cropped area vary annually?

- how much?
- what are the main factors affecting the cropped area?

What is the typical crop rotation in which onions are included?

Cultivation practices and crop development

What is the initial plant density for brown seeds / brown sets / red seeds / red sets?

What is the targeted plant density?

What is the beds' width? Does it affect yield?

What are the approximate planting dates for sets and seeds?

What are the desired conditions for planting/drilling? Rank them according to importance
Soil Temperature / Soil Moisture / Air temperature / Weather forecast Soil tillage

Which development stages and approx. duration do you distinguish?

Does water affect bulbing? How?

Does water affect the time when maturity is reached? How?

What is the typical length of the growing cycle in days?

- For onions grown from seeds
- From sets

What is the harvest's trigger in % of fall-over?

What are the main factors that have changed over the last 10 years in terms of irrigation management on onions?

What are the important future challenges facing UK onion production?

Soils

Does yield vary according to soil type?

Do you think farmers try to minimise the effects of in-field soil variability?

In case of having water restrictions, do you think growers would choose irrigating onions over the other crops?

Do you have any evidence of irrigation impact on onion yield?

Varieties

Have varieties changed over the years?

Which are the most popular? Why?

Post Harvest / Quality

How does price vary with size?

Which are the main factors affecting storage?

Does price change with any other factors?

Could you link penalties in quality with:

- Irrigation scheduling
- Irrigation timing

A.3 Questionnaire 3 Questionnaire targeting INDUSTRY

Date:

Location:

Company

Person interviewed: Job role:

1.General Aspects

Could you give me an overview of how your company works?

Which steps go onions through from arrival to departure?

Do you store as well?

What is the annual volume of onions you process?

Usually, from how many growers do you buy your stock?

Are those growers from this region?

2. Arrival from the field

What is our relationship with the growers?

What is the relationship with the producers?

Are there pre-established...

- Varieties
- Volume of product?

What is the approximate harvest time?

Which are your quality standards?

Is there a quality control at arrival?

What is the procedure at the quality control? What is checked / measured?

What happens if standards are not reached?

How do you decide price?

3. Packing / Processing

Is there any classification upon arrival?

Do different varieties get treated differently?

Are there different quality standards for different varieties?

Are there quality controls along the process?

If yes, at which stage and what gets checked?

What are your end products?

Are there losses along the packing process? Y / N

What is the approximate percentage of losses?

What do they depend on?

Which quality standards do you target with your final product?

4. Storage (only if applicable)

Which varieties go into storage?

Which can be stored for longer?

What affects their storability?

Do you know of any field conditions, which would allow better storage? Any particular soil type or irrigation practices?

Are there any parameters monitored during storage? (T, RH...)

Is there any pre-selection before storage?

Drivers to sell to stored onions?

5. Final product

Who are your clients?

What are your customer's requirements? Rank the following according to importance: High volume / Early supply / Late supply / Specific size / Disease free / Homogeneous size / Colour / Storability / Other

What affects prize?

How does it vary through the year?

6. Onion growing

Are you in touch with growers during the growing season?

Are you aware of their daily problems?

Do they usually irrigate?

Could you tell the difference between irrigated and non-irrigated onions?

And between onions grown on different soils?

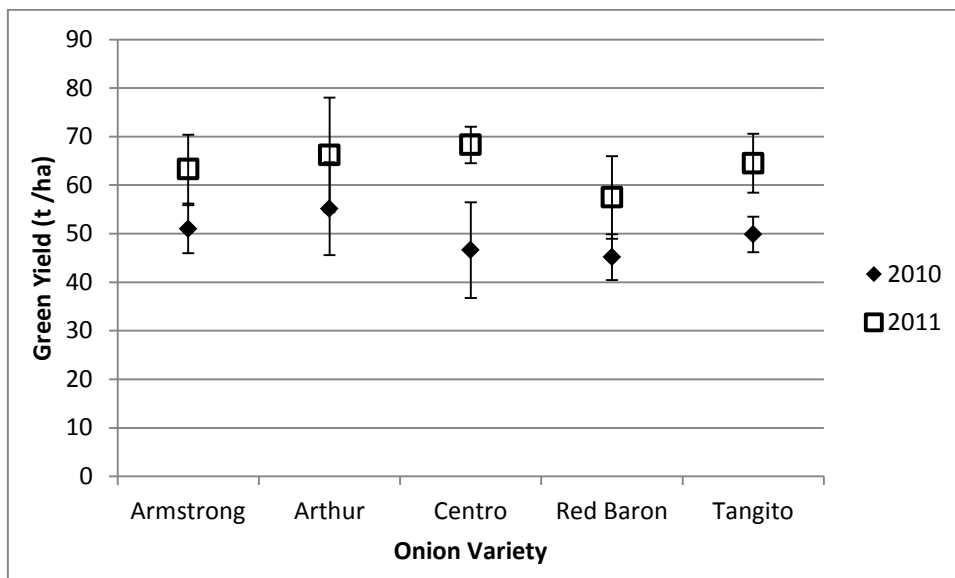
Growers deal with soil problems on their fields. Which are the most quality damaging ones?
Could you rank the following? Soil clay content / Soil sand content / Low/high OM content /
Slope / Waterlogging / Soil acidity/alkalinity / Shallowness /soil depth / Compaction / Crusting /
Stoniness / Restrictive soil horizon / Others

A.4 Case study: yield variability onion yield in Elveden

Thanks to the collaboration of Elveden Estate growers, an ample set of files concerning farm management practices, cultivated varieties and production was available. During the last years, individual field records were carefully annotated. Those include planting dates and varieties; amendments and fertilization application; irrigation dates and depths, and fresh yield production.

Provided onion yield data by the commercial farm included grown varieties, planted surface, harvest yield, and a summary of management practices. Those data provided a good estimate on the actual yield production of many varieties in the Norfolk region. Such a complete data set was available for the years 2010 and 2011.

Elveden yield records showed variability in onion yield of 10-25 t of fresh green yield per ha (see Fig_Apx 1). Some varieties showed greater variability (Centro and Arthur) than others (Tangito, Red Baron and Armstrong).



Fig_Apx 1 Green yield (t/ha) for the main grown varieties in Elveden Estate in 2010 and 2011

Appendix B : Crop growth model identification

B.1 Single crop models for onion

Some models have been exclusively developed to simulate onion crop development, yield production or other crop responses to environment. Those are described underneath.

The ALCEPAS model is one of the single crop models developed for onion production. ALCEPAS (de Visser, 1994a) simulates potential crop growth when weeds, pests, diseases and soil conditions are not limiting factors and there is ample supply of water and nutrients. ALCEPAS simulates potential dry-matter growth and development, according to incoming radiation, day length, temperature, and crop physiological characteristics. De Visser (1994a) parameterized crop functions such as growth, maintenance and growth respiration, leaf area dynamics, death rate of leaves, and photosynthesis parameters.

ALCEPAS growth model was validated using data of leaf area index, bulb and green leaf dry-matter production, bulb formation and day of fall-over from independent trials (de Visser, 1994b). The model performance was good under environmental conditions close to the optimum, but insufficient under stress situations. The model overestimated leaf area index and green leaf dry matter. Bulb formation was simulated satisfactorily, while the time of 50% fall-over was simulated too early at low plant densities.

After the calibration, de Visser (1994b) concludes that ALCEPAS simulates growth and development at a potential production level because only the external factors temperature and light influence yield and development. Limitations of the model rely on daylength sensitivity; the model is limited to daylength requirements similar to cv. 'Rijnsburger-Robusta'.

De Visser and van den Berg (1998) developed a mathematical method able to predict the grade distribution of onions based on the total yield and plant density.

Total onion yield is the result of plants' density and mean size onions. With increasing plant density, onion bulb size decreases. The developed approach would allow using ALCEPAS model results (total field bulb dry weight) to estimate size distribution as well as absolute onion production in different size classes (de Visser and van den Berg, 1998).

B.2 Multiple-crop models

There is a wide range of multi-crop functioning software. Thus could be parameterized to simulate different crops. A lot of work has been done regarding the parameterization and validation of different models to specific crops and locations.

Aqua Crop

AquaCrop is a multi-year, multi-crop, daily-time step simulation model developed by FAO (Raes *et al.*, 2009; Steduto *et al.*, 2009). It is a canopy-level and engineering type of model, focuses on simulating yield in response to available water (Steduto *et al.*, 2009). The interface is user-friendly and parameterisation is easy. It simulates yield response to water of herbaceous crops, and it is particularly suited to address conditions where water is a key limiting factor. One of its more useful features is that compares actual with attainable yield.

Regarding crop management, it allows the simulation of a wide variety of irrigation scheduling (specific events/time/deficit) and application methods (surface, drip, sprinkler...), soil fertility, mulches, field surface practices..

AquaCrop was developed in 2009, and since it has been used with research purposes in over 25 studies. It was proven to predict wheat yield response to different water regimes (Andarzian *et al.* 2011; Salemi *et al.*, 2011), rapeseed

yield (Zeleeke *et al.*, 2011), and maize, sugar beet and sunflower production under different climatic conditions (Stricevic *et al.* 2011). The model was calibrated and validated for barley (Araya *et al.*, 2010), teff (Araya *et al.*, 2010) and Bambara groundnut (Karunaratne *et al.*, 2011). Its adequacy to be used as a management tool – especially at irrigation scheduling - has been confirmed after its calibration for the previously mentioned crops.

These results have been published in journals such as European Journal of Agriculture, Field Crops Research, and Agricultural Water Management.

CropSyst (Crop Systems Simulation Model)

CropSyst (Stöckle *et al.*, 2003) is a multi-year, multi-crop, daily-time step simulation model developed by the Biological Systems Engineering Department at Washington State University. It has a friendly user interface and can be linked to GIS software.

CropSyst simulates soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water and pesticide fate. The model inputs are weather, soil and crop characteristics, and cropping system management (crop rotation, cv., irrigation, N fertilization, soil and irrigation water salinity, tillage operations and residue management).

This software has been used to simulate a wide range of herbaceous crops such as maize, wheat, rice, tomato, oats, rye grass, cotton and alfalfa. It includes the parameters for garlic crop simulation, which as onion is another *Allium* bulbing crop.

DNDC

DNDC (DeNitrification-DeComposition) is a simulation tool for carbon and biochemistry in agro-ecosystems. The model can be used to predict crop growth and yield production, soil carbon dynamics, nitrogen leaching and gas emissions (<http://www.dndc.sr.unh.edu/>). It was developed in 1994 and since

then it has been mainly used in the assessment of the effects of management practices in gas emissions in rice (Yu *et al.*, 2011) , grasslands (Abdalia *et al.*, 2010; Rashad *et al.*, 2011) and general arable and farming systems (Marco *et al.*, 2011; Bernard *et al.*, 2011; Adballa *et al.*, 2009).

In its package, it includes onion crop parameters, however, no validation of these values could be found. This software has been used as a tool in environmental studies and not in farm management.

DSSAT: CROPGRO

DSSAT (Decision Support System for Agrotechnology Transfer) was developed in 1991 to serve as a management tool in farming and other rural related activities. As the previously mentioned software, it allows a wide set of input data, as well as parameterization. It includes packages for the simulation of wheat, maize, soybean, rice, groundnut, dry bean, sorghum and millet (Saseendran *et al.*, 2009; Staggenborg and Vanderlip, 2003). Lately another package was included, thus allows the simulation of several vegetables. Neither onion nor any other Allium is included.

MOPECO

MOPECO is an economic and irrigation management model, which serves as a tool for irrigation optimisation. It consists of 3 modules. The first module estimates irrigation needs. Module 2 simulates the irrigation uniformity distribution and estimates the gross margin taken economic and yield data into account. Module 3 identifies cropping patterns and irrigation strategies, which would maximise profits (Ortega-Alvarez *et al.*, 2004). MOPECO has been used and compared to other models for onion production under salinity conditions (Dominguez *et al.*, 2011).

Other Models

There are other models that focus on a single parameter e.g. Greenwood *et al.* (2001a). The authors developed a mechanistic model to calculate the effects of

P fertilizer on arable cropping. It simulates the crop response to starter fertilizer, later applications and on growth and plant P concentrations during the entire period of growth.

The model was calibrated for several vegetable crops such as onion, leek and spinach (Greenwood 2001b). The model gave satisfactory predictions of the time course of dry weight and plant % P from emergence to commercial harvest. The model could form the basis of a short-cut approach forecasting optimal fertilizer P practices for different crops in different soils (Greenwood 2001b).

For irrigation scheduling purposes, models should simulate growth and development. FAO recommend semi-empirical approaches for calculating crop water requirements.

Jovanovic and Annandale (1999) determined water requirements for vegetables and developed a simple, generic crop irrigation scheduling model for vegetables grown in South Africa. A database including basal crop coefficients (K_{cb}) values, growth periods, root depths and crop height would be generated.

Other software have been involved in the simulation and evaluation of different production alternatives. Patel and Rajput (2008) for instance, used Hydrus 2D to simulate subsurface drip irrigation in onions. It would serve as a tool to evaluate different depths of irrigation laterals and distance between them.

Randle (1990) developed a computer-based model to simulate the effects of precision planting on onion quality and yield. He found out that the most influencing parameters were seed germination, plant survival, planter efficiency, onion growth potential, maximum onion size, sizing potential and inside-outside bed effects.

A study was carried out by Tei *et al.* (1996) to determine growth, development and light interception parameters for lettuce, red beet and onion. The results of this study were considered in other stages of this study.

All the previously mentioned models and some of their characteristics have been summarized in the following matrix to assess their suitability in this study (see Table_Apx 1).

B.3 Model Identification

AquaCrop appeared to be one of the most suitable models to achieve this study's aim. However, no study involving onion simulations was found. Thus crop parameters had to be identified and the model calibrated and validated using experimental data.

The criteria used to select a suitable model were presented in Table_Apx 1. Some of the desired characteristics included daily time step simulation, water balance and crop response to water inputs, actual vs. potential yield and canopy cover, yield production, and other input options regarding soil and crop characteristics.

Considering all these issues, **AquaCrop** was identified as the most suitable models for this study.

Table_Apx 1 Model features matrix

Model	Daily time step simulation	Water balance and crop response to water inputs	Actual vs. potential yield/canopy cover	Yield production	Size distribution	Fertilisation	Soil characteristics	Previously used for onions/allium	Model package includes onion parameters	Availability	Easy interface	Easy parameterisation	Contact with developers
ALCEPAS	Y	N	N	Y	N	N	N	Y	Y	N			N
AquaCrop	Y	Y	Y	Y	N	Y	Y	N	N	Y	Y	Y	Y
CROPGRO	Y	Y		Y		Y	Y	N	N	I			Y
CropSyst	Y	Y		Y		Y	Y	Y*	N	Y	N	N	
De Visser and van den Berg, 1998	N	N	N	N	Y	N	N	Y	Y	N			N
DNDC	Y	Y	Y	Y	N	Y	Y		Y	Y	Y	Y	N
Greenwood <i>et al.</i> , 2001		N				Y				N			
MOPECO	Y**	N	N	N	N	N	N			Y			Y

*Garlic, **crop water requirements estimation

Table_Apx 1 presents eight of the previously mentioned models and indicates with a Y (yes) and N (no) if they fulfil the listed features. The characteristics the models were assessed for are the following:

- Daily time step simulation: to have a better understanding and allow comparison with observed data, it is necessary that the model makes the calculations in daily steps and gives daily intermediate results.
- Water balance and crop response to water inputs: the objective of this study is to identify the effects of irrigation and crop water status affecting yield
- Actual vs. potential yield/canopy cover: in order to optimize the resources, it is important to compare the actual performance against the potential
- Yield production: yield is the main output of commercially grown crop, and farm management looks into maximizing it
- Size distribution: this is not an essential feature for the chosen model, but it might be useful
- Fertilisation: to study the effects of fertilizer use and optimize its application
- Soil characteristics: To reproduce real conditions, as water, plants, and nutrients behave different from one soil to another. To identify the effects of in-field soil variability.
- Previously used for onions/allium: there would be guidelines or experts
- Model package includes onion parameters: calibration would be easier if the model had been used before with similar purposes
- Availability: the model should be existing and available
- Easy interface: a simple use would make it a potential tool for growers
- Easy parameterisation: changing parameters easily would allow a better and easier work
- Contact with developers: to ask for advice or doubts

Appendix C : Data for model calibration

C.1 Irrigation treatments in Broom's Barn Research Centre

AWC stands for Available Water Content within the rooting zone (assumed to be 30 cm) FC is the Field Capacity within the rooting zone (assumed to be 30cm), and FO stands for fall-over

Table_Apx 2Irrigation regimes in Broom's Barn Research Centre in 2010 (FV362a, annual report, year 1

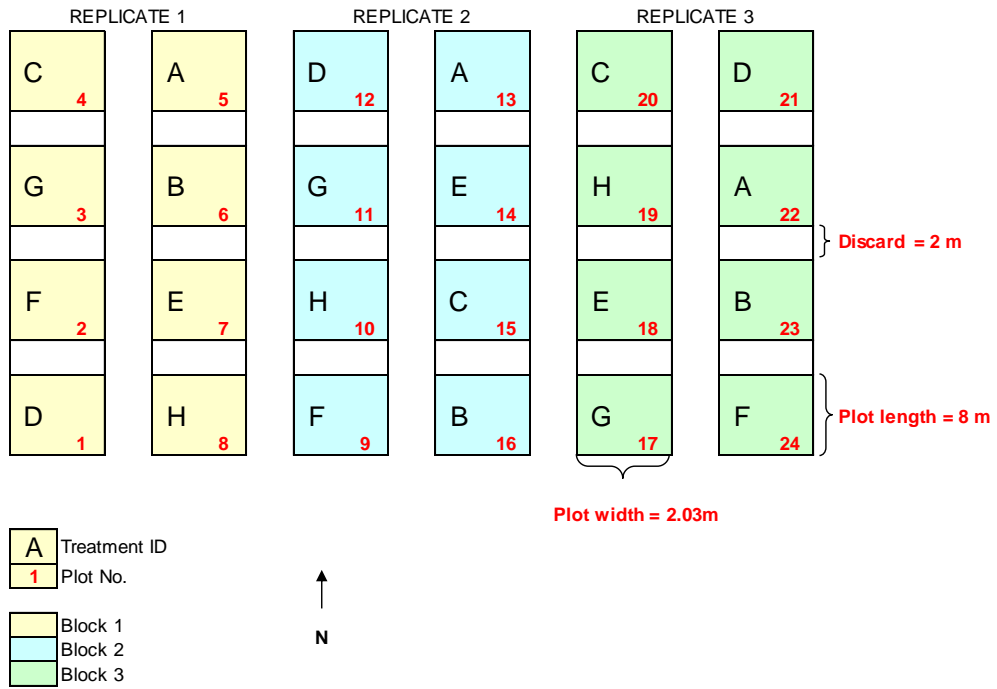
Treatment	Name	Irrigation from start of season to bulb initiation	Irrigation from bulb initiation	Stop irrigation at
A	Typical	Return to FC at deficit of 50% AWC	Return to FC at deficit of 75% AWC	50% fall-over
B	Typical, no extra stress	Return to FC at deficit of 50% AWC	Return to FC at deficit of 50% AWC	50% fall-over
C	Typical, no extra stress, extended	Return to FC at deficit of 50% AWC	Return to FC at deficit of 50% AWC	100% fall-over and 50% dead
D	Less more often, no extra stress	Return to FC at deficit of 25% AWC	Return to FC at deficit of 25% AWC	50% fall-over
E	Less more often, no extra stress, extended	Return to FC at deficit of 25% AWC	Return to FC at deficit of 25% AWC	100% fall-over and 50% dead
F	Excess	Return to FC at deficit of 12.5% AWC	Return to FC at deficit of 12.5% AWC	100% fall-over and 50% dead
G	Stress	Return to FC at deficit of 75% AWC	Return to half of deficit at 75% AWC	50% fall-over
H	No irrigation	-	-	-

**Table_Apx 3 Irrigation regimes in Broom's Barn Research Centre in 2011
(FV362a, annual report, year 2**

Trt	Name	Late May to initiation (E July)		Initiation (E July) to egg stage (E Aug)		Egg stage (E Aug) to stop (50% FO)		Stop
		Trigger	Target App	Trigger	Target App	Trigger	Target App	
A	Typical, end season stress	50% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
B	Typical with mid & end season stress	50% AWC	Return to FC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
C	Typical with early & end season stress	75% AWC	50% of AWC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
D	Less more often, no stress	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	50% FO
E	Less more often, end season stress	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	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	75% AWC	50% of AWC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
H	Stress all season	75% AWC	50% of AWC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO

E: early; L : Late

C.2 Irrigation trials' plot's layout in Broom's Barn Research Centre



Lacey & Ober (2011)

C.3 Onion DM determination

In September 2012, 5 plants were randomly sampled from each of the experimental plots to determine DM content. Plants were weighted before and after drying them in the oven for 48h. DM was calculated dividing water content by fresh weight (DM=(fresh weight – dry weight / fresh weight)

The following table (Table_Apx 4) presents the results of the DM determination.

Table_Apx 4 Bulb diameter (mm), fresh and dry weight of bulbs and leaves (g), and DM (%)

Treatment	Bulb D (mm)	Fresh weight (g)		Dry weight (g)		DM (%)
		Bulb+Neck	Leaves	Bulb+Neck	Leaves	
A	65.85	163.79	52.40	22.40	5.28	12.91
B	67.12	170.18	42.58	23.33	4.49	13.28
C	68.05	173.36	56.84	24.25	5.63	13.05
D	68.45	172.84	41.57	22.77	4.85	13.02
E	61.04	135.30	47.58	18.30	4.98	12.87
F	66.43	158.66	60.90	20.14	6.15	12.15
G	63.14	136.95	36.53	18.87	4.07	13.27
H	67.15	168.48	60.77	23.49	6.16	13.04
Grand Total	65.91	158.65	49.90	21.52	5.20	12.95

Appendix D : AquaCrop parameters

D.1 Crop parameters

AquaCrop

3.1: AquaCrop Version 3.1plus (January 2011)

1: File not protected

3: root/tuber crop

1: Crop is sown

0: Determination of crop cycle : by growing degree-days

1: Soil water depletion factors (p) are adjusted by ETo

6.0: Base temperature (°C) below which crop development does not progress

30.0: Upper temperature (°C) above which crop development no longer increases with an increase in temperature

1450: Total length of crop cycle in growing degree-days

0.30: Soil water depletion factor for canopy expansion (p-exp) - Upper threshold

0.65: Soil water depletion factor for canopy expansion (p-exp) - Lower threshold

3.0: Shape factor for water stress coefficient for canopy expansion (0.0 = straight line)

0.50: Soil water depletion fraction for stomatal control (p - sto) - Upper threshold

3.0: Shape factor for water stress coefficient for stomatal control (0.0 = straight line)

0.92: Soil water depletion factor for canopy senescence (p - sen) - Upper threshold

3.0: Shape factor for water stress coefficient for canopy senescence (0.0 = straight line)

0: Sum(ETo) during stress period to be exceeded before senescence is triggered

0.90: Soil water depletion factor for pollination (p - pol) - Upper threshold

5: Vol% for Anaerobic point (* (SAT - [vol%]) at which deficient aeration occurs *)

50: Soil fertility stress at calibration (%)

25.00: Shape factor for the response of canopy expansion for limited soil fertility

25.00: Shape factor for the response of maximum canopy cover for limited soil fertility

25.00: Shape factor for the response of crop Water Productivity for limited soil fertility

25.00: Shape factor for the response of decline of canopy cover for limited soil fertility

8: Minimum air temperature below which pollination starts to fail (cold stress) (°C)

40: Maximum air temperature above which pollination starts to fail (heat stress) (°C)

6.0: Minimum growing degrees required for full biomass production (°C - day)

0.95: Crop coefficient when canopy is complete but prior to senescence (Kcb,x)

0.800: Decline of crop coefficient (%/day) as a result of ageing, nitrogen deficiency, etc.

0.20: Minimum effective rooting depth (m)

0.35: Maximum effective rooting depth (m)

30: Shape factor describing root zone expansion

0.057: Maximum root water extraction (m³water/m³soil.day) in top quarter of root zone

0.015: Maximum root water extraction (m³water/m³soil.day) in bottom quarter of root zone

60: Effect of canopy cover in reducing soil evaporation in late season stage

5.00: Soil surface covered by an individual seedling at 90 % emergence (cm²)

520000: Number of plants per hectare

0.07272: Canopy growth coefficient (CGC): Increase in canopy cover (fraction soil cover per day)

-9: Maximum decrease of Canopy Growth Coefficient in and between seasons
- Not Applicable

-9: Number of seasons at which maximum decrease of Canopy Growth Coefficient is reached - Not Applicable

-9.0: Shape factor for decrease Canopy Growth Coefficient - Not Applicable

0.65: Maximum canopy cover (CCx) in fraction soil cover

0.04395: Canopy decline coefficient (CDC): Decrease in canopy cover (in fraction per day)

33: Calendar Days: from sowing to emergence

83: Calendar Days: from sowing to maximum rooting depth

164: Calendar Days: from sowing to start senescence

186: Calendar Days: from sowing to maturity (length of crop cycle)

124: Calendar Days: from sowing to start of yield formation

0: Length of the flowering stage (days)

0: Crop determinancy unlinked with flowering

9: Excess of potential fruits - Not Applicable

57: Building up of Harvest Index starting at root/tuber enlargement (days)

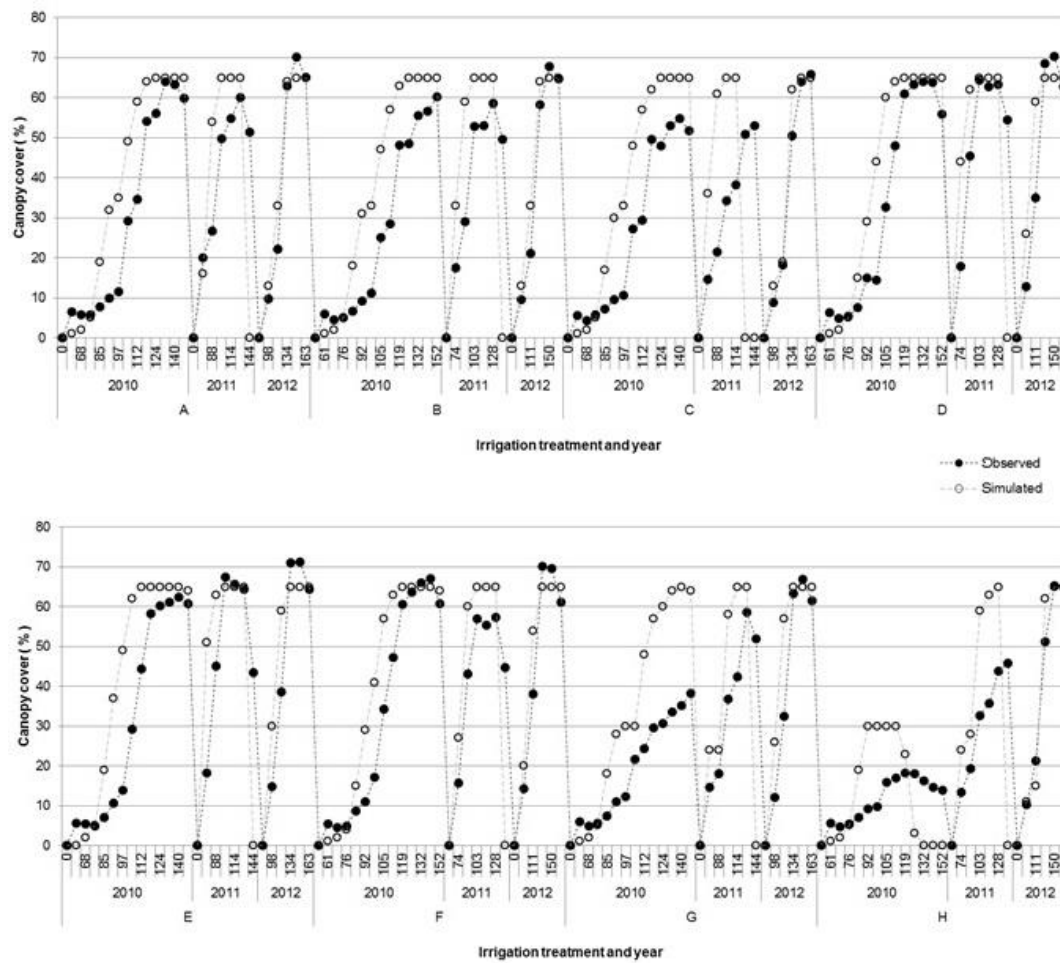
18.0: Water Productivity normalized for ETo and CO₂ (WP*) (gram/m²)

100: Water Productivity normalized for ETo and CO₂ during yield formation (as % WP*)

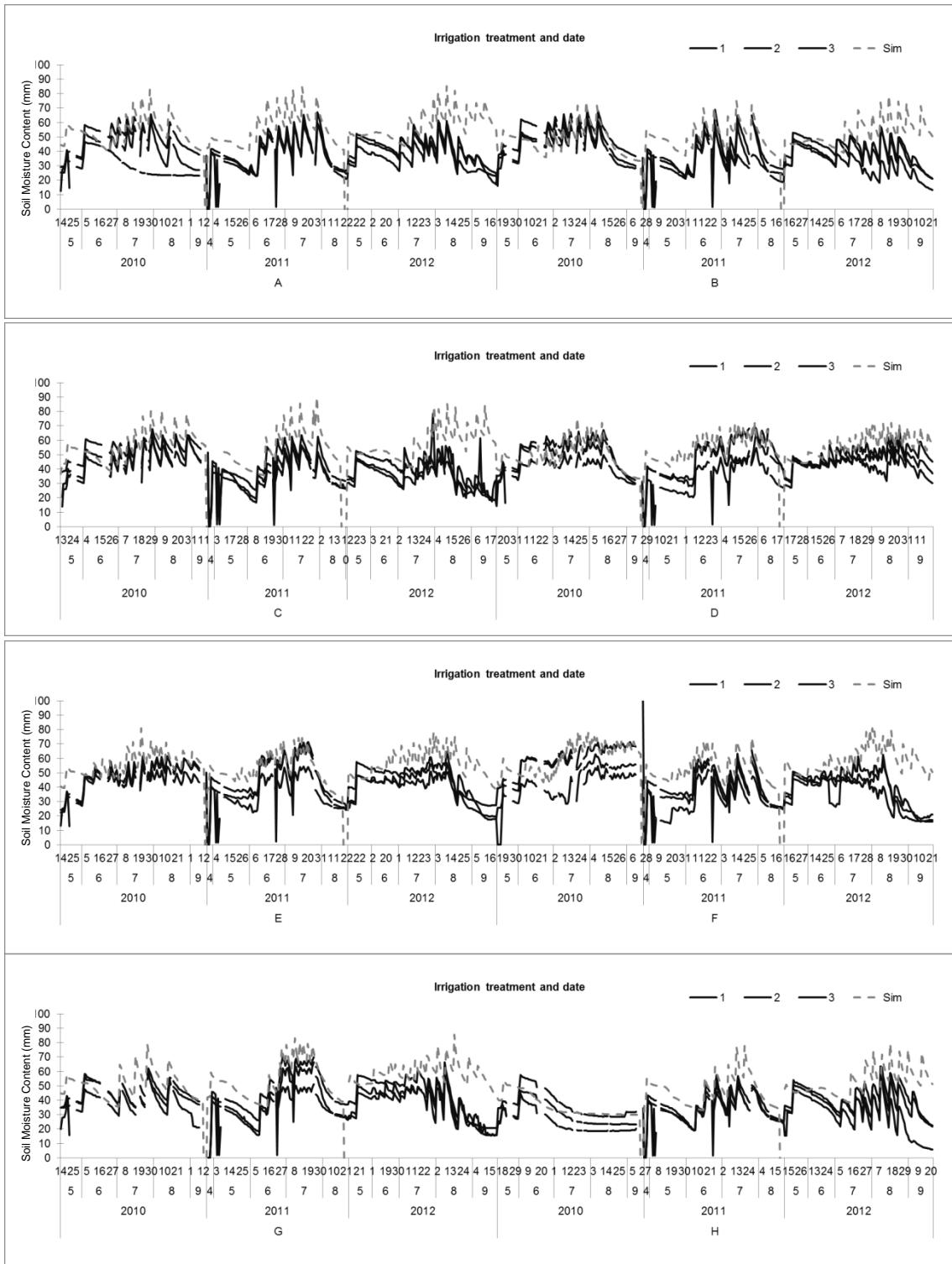
80: Reference Harvest Index (Hlo) (%)

0: Possible increase (%) of HI due to water stress before start of yield formation
4.0: Coefficient describing positive impact on HI of restricted vegetative growth during yield formation
5.0: Coefficient describing negative impact on HI of stomatal closure during yield formation
8: Allowable maximum increase (%) of specified HI
60: GDDays: from sowing to emergence
343: GDDays: from sowing to maximum rooting depth
1263: GDDays: from sowing to start senescence
1450: GDDays: from sowing to maturity (length of crop cycle)
816: GDDays: from sowing to start tuber formation
0: Length of the flowering stage (growing degree days)
0.009803: CGC for GDDays: Increase in canopy cover (in fraction soil cover per growing-degree day)
0.005451: CDC for GDDays: Decrease in canopy cover (in fraction per growing-degree day)
606: GDDays: building-up of Harvest Index during yield formation

D.2 Simulated and observed CC and SMC values for 2010, 2011 and 2012



Fig_Apx 2 Average observed and simulated canopy cover for the irrigation treatments A, B, C, D, E, F, G, and H in 2010, 2011, and 2012



Fig_Apx 3 Simulated and observed soil moisture content in the root zone in the 3 plots for the irrigation regimens A, B, C, D, E, F, G, and H in 2010, 2011, and 2011

Appendix E Irrigation Evaluation

E.1 Boom

Three evaluations on a boom irrigation system were conducted in Elveden Estate, Norfolk, on the 9th, 19th, and 28th July 2010 by the author of this thesis.

Table_Apx 5 Volume collected in each catch-can at the irrigation evaluations conducted to a boom system, in three different dates.

Distance to the centre of the boom (m)	T 1	T 2	T 3	Distance to the centre of the boom (m)	T 1	T 2	T 3
-44	0.63	0.83	0	-16	13.36	15.70	14.32
-42	2.56	2.75	0	-14	13.36	14.05	16.53
-40	4.05	3.86	0	-12	14.60	17.35	15.70
-38	6.61	10.60	0	-10	13.50	13.50	13.50
-36	8.40	9.09	0.28	-8	14.32	15.70	13.36
-34	10.19	9.37	2.62	-6	11.71	14.05	15.15
-32	10.54	10.19	7.02	-4	13.77	19.01	20.11
-30	14.12	13.50	11.71	-2	15.42	16.53	18.73
-28	16.11	16.80	14.05	0	26.99	25.34	23.14
-26	17.63	17.90	12.95	2	17.77	12.95	17.35
-24	17.70	19.28	15.15	4	13.77	19.28	18.45
-22	14.46	16.25	14.32	6	11.43	13.50	12.95
-20	11.71	16.11	15.42	8	14.19	15.42	16.53
-18	11.36	14.87	14.87	10	14.46	15.42	16.11

Distance to the centre of the boom (m)	T 1	T 2	T 3
12	16.94	18.18	18.45
14	15.42	15.42	16.25
16	15.56	16.25	16.25
18	14.60	14.87	16.11
20	16.25	19.01	16.25
22	14.74	15.15	13.22
24	16.66	17.63	13.77
26	15.84	17.08	11.84

Distance to the centre of the boom (m)	T 1	T 2	T 3
28	16.39	17.35	12.67
30	13.77	14.87	9.37
32	10.88	11.84	3.31
34	11.71	11.02	0
36	12.12	13.77	0
38	8.54	10.74	0
40	4.96	7.99	0
42	2.07	4.41	

E.2 Linear move

Three evaluations on a linear move irrigation system were conducted. Irrigation application was assessed in Elveden Estate, Norfolk, on the 21st August 2012, and on the 10th July, 2013.

21st August 2012, Yorks Field, Elveden Estate, Suffolk

Table_Apx 6 Results for the applied irrigation depth at the irrigation evaluations (21/8/2012 and 10/7/2013). Irrigation depth (mm) per catch can and distance to edge

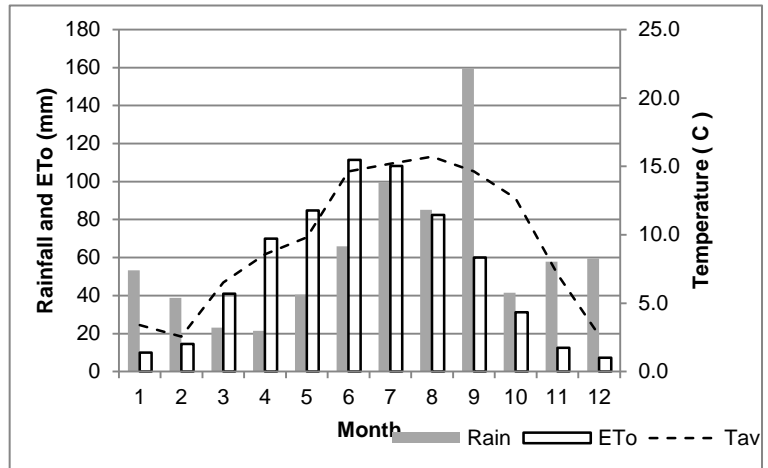
08/2012 (2 reps)			07/2013		08/2012 (2 reps)			07/2013	
d (m)	depth (mm)	depth (mm)	d (m)	depth (mm)	d (m)	depth (mm)	depth (mm)	d (m)	depth (mm)
0	14.93	14.8	0.0	15.40	130	10.66	12.25	47.6	12.09
5	13.85	13.21	1.8	16.71	135	32.05	16.87	49.4	12.67
10	18.59	14.48	3.7	13.94	140	11.46	10.92	51.2	14.64
15	15.6	13.85	5.5	12.03	145	14.64	14.48	53.1	14.80
20	14.8	13.69	7.3	14.04	150	11.62	15.34	54.9	10.50
25	15.6	14.16	9.2	16.87	155	14.01	14.48	56.7	9.48
30	15.28	14.8	11.0	14.00	160	14.32	14.16	58.6	11.94
35	16.07	14.16	12.8	10.88	165	13.85	12.1	60.4	13.24
40	13.85	13.05	14.6	11.74	170	13.69	12.89	62.2	14.64
45	11.62	11.3	16.5	13.94	175	13.85	14.32	64.1	15.21
50	15.44	14.16	18.3	17.50	180	13.69	13.69	65.9	13.72
55	13.85	14.01	20.1	13.91	185	9.71	12.41	67.7	16.30
60	16.39	13.53	22.0	12.54	190	14.32	5.57	69.5	18.91
65	17.51	14.48	23.8	14.96	195	12.57	7.16	71.4	12.41
70	16.07	14.48	25.6	14.35	200	11.62	8.91	73.2	13.40
75	13.69	12.89	27.5	15.72	205	13.53	14.8	75.0	18.62
80	15.92	13.75	29.3	13.49	210	14.96	13.05	76.9	15.28
85	17.76	14.2	31.1	12.06	215	14.8	15.76	78.7	13.56
90	13.53	13.27	32.9	16.17	220	12.73	12.57	80.5	13.78
95	16.71	13.37	34.8	16.65	225	12.1	12.57	82.4	14.13
100	7.8	11.14	36.6	14.61	230	15.28	15.12	84.2	16.45
105	13.05	11.78	38.4	9.90	235	14.16	13.21	86.0	14.48
110	17.51	14.96	40.3	10.82	240	13.21	14.01	87.8	14.10
115	16.07	17.63	42.1	14.23	245	13.21	12.41	89.7	13.91
120	14.64	14.96	43.9	14.48	250	12.73	12.25	91.5	14.10
125	12.1	16.81	45.8	12.95	255	14.01	23.55	93.3	14.26

08/2012 (2 reps)			07/2013		08/2012 (2 reps)			07/2013	
d (m)	depth (mm)	depth (mm)	d (m)	depth (mm)	d (m)	depth (mm)	depth (mm)	d (m)	depth (mm)
260	13.69	12.73	95.2	13.62				150.1	17.60
265	14.32	13.53	97.0	15.79				151.9	15.15
270	13.53	14.16	98.8	18.24				153.7	13.84
275	14.32	13.69	100.7	19.19				155.6	14.93
280	13.21	13.69	102.5	14.83				157.4	17.76
285	13.69	13.21	104.3	14.32				159.2	18.08
290	12.73	14.01	106.1	13.53				161.0	13.08
295	13.85	11.14	108.0	15.37				162.9	15.91
300	14.96	14.48	109.8	14.29				164.7	18.78
305	10.19	11.62	111.6	11.84				166.5	22.82
310	13.85	11.46	113.5	12.35				168.4	18.46
315	11.46	13.05	115.3	15.56				170.2	17.19
320	12.73	11.94	117.1	18.49				172.0	18.27
325	11.78	15.28	119.0	14.48				173.9	19.10
330	10.82	12.41	120.8	14.64				175.7	19.10
335	12.41	12.73	122.6	15.02				177.5	13.59
340	10.35	14.32	124.4	18.01				179.3	13.08
345	20.53	11.52	126.3	19.38				181.2	14.77
350		20.12	128.1	14.64				183.0	18.56
355		22.6	129.9	14.35				184.8	15.12
			131.8	16.77				186.7	13.53
			133.6	18.94				188.5	14.16
			135.4	13.53				190.3	16.74
			137.3	12.29				192.2	19.41
			139.1	13.53				194.0	15.88
			140.9	21.39				195.8	13.14
			142.7	18.43				197.6	15.66
			144.6	15.21				199.5	16.87
			146.4	15.37				201.3	18.71
			148.2	17.60				203.1	13.91

Appendix F : Weather data

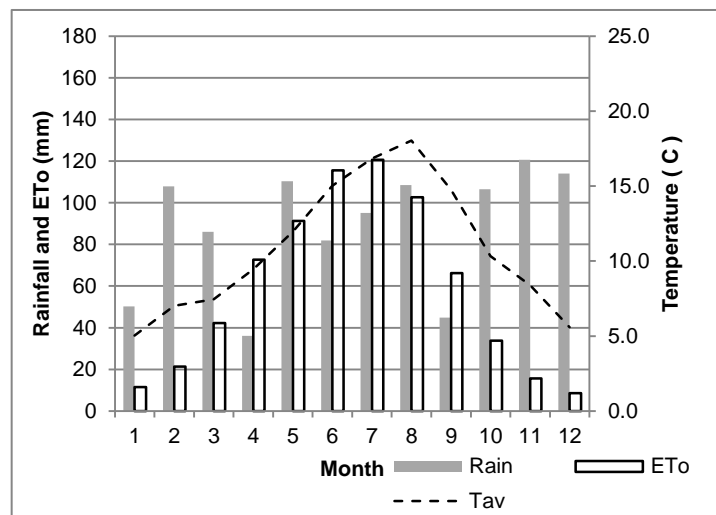
F.1 Very wet year

Month	Rain	ETo	Tav
1	53.4	10.0	3.4
2	38.8	14.5	2.6
3	23.2	41.0	6.5
4	21.5	70.0	8.6
5	40.5	84.8	9.8
6	66.0	111.3	14.6
7	99.7	108.2	15.2
8	85.2	82.4	15.7
9	159.5	60.0	14.6
10	41.5	31.3	12.7
11	57.9	12.6	7.1
12	59.6	7.2	2.7
Total	746.4	633.4	9.5



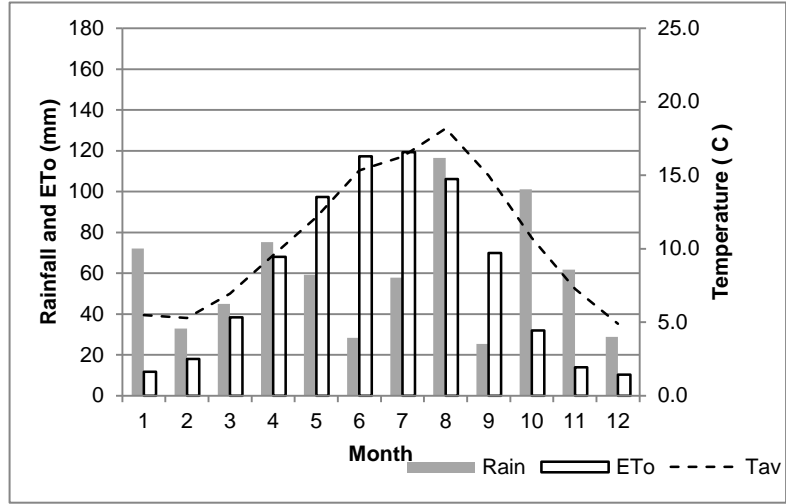
F.2 Average wet year

Month	Rain	ETo	Tav
1	50.3	11.5	5.0
2	108.0	21.4	7.0
3	86.1	42.3	7.4
4	36.2	72.7	9.5
5	110.4	91.3	12.0
6	82.0	115.6	15.0
7	95.2	120.7	16.9
8	108.5	102.7	18.0
9	44.8	66.2	14.7
10	106.5	33.8	10.3
11	120.7	15.6	8.4
12	114.1	8.5	5.6
Total	1062.6	702.2	10.8



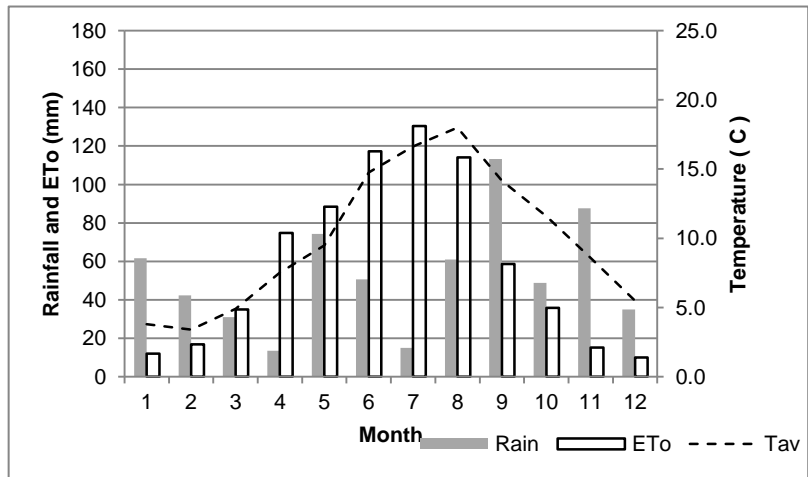
F.3 Average year

Month	Rain	ETo	Tav
1	72.2	11.8	5.5
2	33.0	18.0	5.3
3	45.0	38.5	7.0
4	75.2	68.1	9.6
5	59.2	97.4	12.1
6	28.4	117.3	15.3
7	57.8	119.4	16.3
8	116.6	106.2	18.2
9	25.4	69.9	15.0
10	101.2	32.0	10.7
11	61.8	13.9	7.3
12	28.8	10.3	4.9
Total	704.6	702.7	10.6



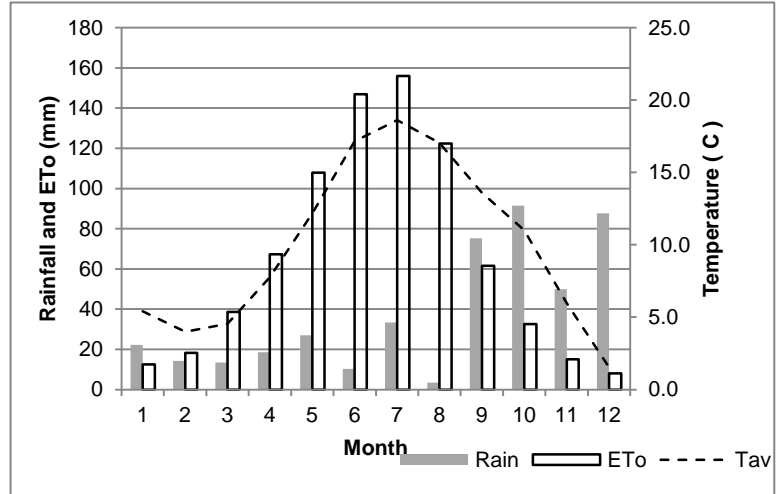
F.4 Average dry year

Month	Rain	ETo	Tav
1	61.6	12.1	3.8
2	42.3	16.9	3.4
3	31.0	35.0	4.9
4	13.6	74.8	7.5
5	74.3	88.4	9.5
6	50.7	117.2	14.8
7	15.0	130.3	16.6
8	60.9	114.0	18.0
9	113.3	58.7	14.2
10	48.9	35.9	11.6
11	87.6	15.2	8.6
12	35.1	10.0	5.5
Total	634.3	708.5	9.9



F.5 Very dry year

Month	Rain	ETo	Tav
1	22.3	12.5	5.4
2	14.2	18.3	4.0
3	13.5	38.6	4.5
4	18.5	67.3	7.8
5	27.0	107.9	12.2
6	10.2	146.9	17.2
7	33.4	155.9	18.6
8	3.5	122.3	17.0
9	75.3	61.6	13.6
10	91.5	32.6	11.0
11	49.9	15.0	6.0
12	87.7	8.0	1.5
Total	447	786.8	9.9



F.6 Reference irrigation schedule

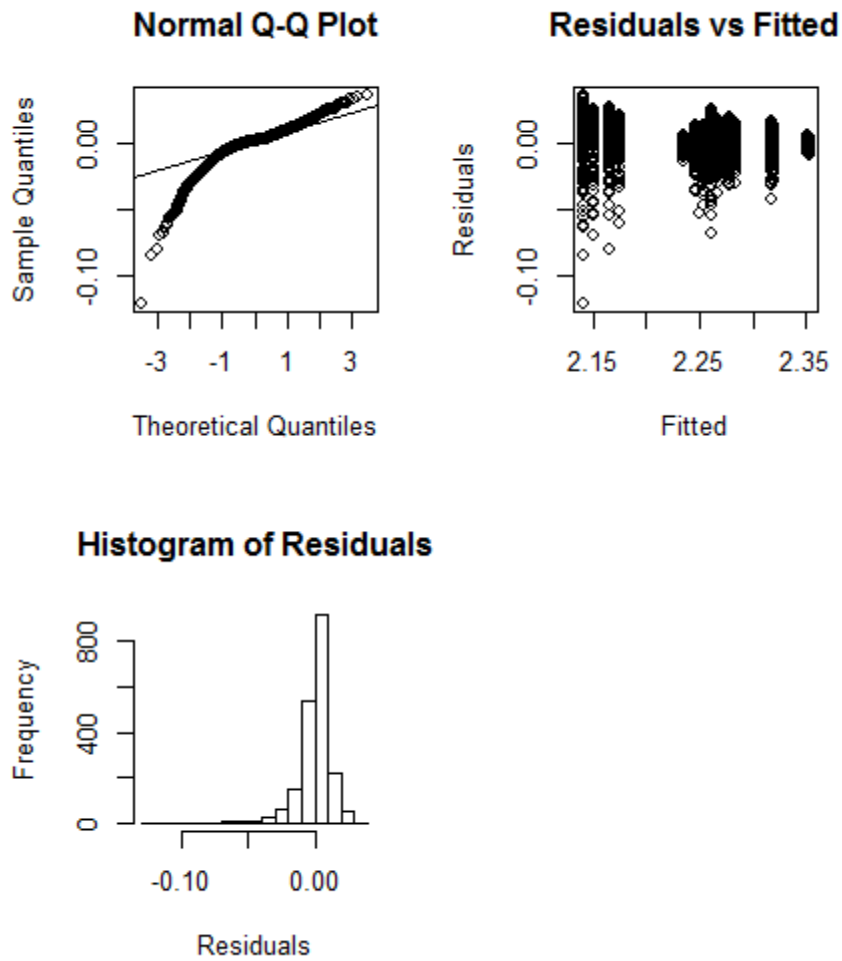
Table_Apx 7 Reference irrigation schedule for a sandy soil and a light sandy loam, during a very wet, average wet, average, average dry, and very dry years. Date of irrigation given as DAP (DAP start on the 1st of March)

Year	SANDY SOIL		SANDY LOAM	
	DAP	Depth (mm)	DAP	Depth (mm)
<u>Very wet</u>	86	14	58	20
	95	14	90	20
	107	14	106	20
	125	14	126	20
	129	14	153	25
	151	20		
	55	14		
Total applications		6		5
Total irrigation needs		90		105
Simulated Yield (kg DM ha⁻¹)		10.528		10.222
<u>Average wet</u>	112	14	55	20
	117	14	114	20
	120	14	120	20
	141	20	142	25
	150	20	152	25
	80	14		
Total applications		6		5
Total irrigation needs		96		110
Simulated Yield (kg DM ha⁻¹)		9.586		9.398
<u>Average</u>	100	14	86	20
	104	14	100	20
	108	14	106	20
	112	14	110	20
	121	14	121	20
	142	20	145	25
	151	20	153	25
	156	20		
	194	20		
	57	14		
Total applications		10		7
Total irrigation needs		164		150
Simulated Yield (kg DM ha⁻¹)		9.632		9.625
<u>Average dry</u>	81	14	57	20
	116	14	81	20
	123	14	112	20

	128	14	120	20
	131	14	128	20
	134	14	132	20
	145	20	141	20
	151	20	147	25
	169	20	153	25
	176	20	171	25
	185	20	179	25
	69	14	197	25
Total applications		12		12
Total irrigation needs		198		265
Simulated Yield (kg DM ha⁻¹)		9.862		9.748
<u>Very dry</u>	95	14	63	20
	101	14	83	20
	107	14	98	20
	116	14	106	20
	119	14	115	20
	121	14	119	20
	124	14	122	20
	126	14	125	20
	130	20	129	25
	134	20	134	25
	144	20	146	25
	151	20	153	25
	158	20	160	25
	165	20	167	25
	171	20	175	25
	179	20	188	25
Total applications		17		16
Total irrigation needs		286		360
Simulated Yield (kg DM ha⁻¹)		8.859		8.733

Appendix G : Statistical Analysis

G.1 Study of the distribution of the residual values



G.2 Results of Kruskal-Wallis test

yield,soil:

Value: 45.86499
degrees of freedom: 1
Pvalue chisq : 1.266898e-11

soil, means of the ranks

	yield	r
sand	1087.9525	1000
sandyloam	913.0475	1000

t-Student: 1.961152
Alpha : 0.05
LSD : 50.07733

Means with the same letter are not significantly different

Groups, Treatments and mean of the ranks

a	sand	1088
b	sandyloam	913

yield,year:

Value: 1704.414
degrees of freedom: 4
Pvalue chisq : 0

year, means of the ranks

	yield	r
A	1799.1925	400
B	800.6950	400
C	897.3375	400
D	1304.7700	400
E	200.5050	400

t-Student: 1.961154
Alpha : 0.05
LSD : 30.77355

Means with the same letter are not significantly different

Groups, Treatments and mean of the ranks

a	A	1799
b	D	1305
c	C	897.3
d	B	800.7
e	E	200.5

yield,irrig:

Value: 4.489858
degrees of freedom: 1
Pvalue chisq : 0.03409652

irrig, means of the ranks

	yield	r
boom	973.138	1000
linear	1027.862	1000

t-Student: 1.961152
Alpha : 0.05
LSD : 50.60497

Means with the same letter are not significantly different

Groups, Treatments and mean of the ranks

a	linear	1028
b	boom	973.1

yield,soil:year

Value: 1841.874
degrees of freedom: 9
Pvalue chisq : 0

soil:year, means of the ranks

	yield	r
sand:A	1900.5000	200
sand:B	1063.7225	200
sand:C	776.7350	200
sand:D	1432.2550	200

sand:E 266.5500 200
 sandyloam:A 1697.8850 200
 sandyloam:B 537.6675 200
 sandyloam:C 1017.9400 200
 sandyloam:D 1177.2850 200
 sandyloam:E 134.4600 200

t-Student: 1.961157
 Alpha : 0.05
 LSD : 31.82416

Means with the same letter are not significantly different

Groups, Treatments and mean of the ranks

a sand:A 1900
 b sandyloam:A 1698
 c sand:D 1432
 d sandyloam:D 1177
 e sand:B 1064
 f sandyloam:C 1018
 g sand:C 776.7
 h sandyloam:B 537.7
 i sand:E 266.6
 j sandyloam:E 134.5

yield,year:irrig

Value: 1711.676
 degrees of freedom: 9
 Pvalue chisq : 0

year:irrig, means of the ranks

	yield	r
A:boom	1795.5300	200
A:linear	1802.8550	200
B:boom	793.0100	200
B:linear	808.3800	200
C:boom	849.5650	200
C:linear	945.1100	200
D:boom	1247.4625	200
D:linear	1362.0775	200
E:boom	180.1225	200
E:linear	220.8875	200

t-Student: 1.961157
 Alpha : 0.05

LSD : 43.03466

Means with the same letter are not significantly different

Groups, Treatments and mean of the ranks

a	A:linear	1803
a	A:boom	1796
b	D:linear	1362
c	D:boom	1247
d	C:linear	945.1
e	C:boom	849.6
ef	B:linear	808.4
f	B:boom	793
g	E:linear	220.9
g	E:boom	180.1

yield,year:irrig:soil

Value: 1849.631
 degrees of freedom: 19
 Pvalue chisq : 0

year:irrig:soil, means of the ranks

	yield	r
A:boom:sand	1900.695	100
A:boom:sandyloam	1690.365	100
A:linear:sand	1900.305	100
A:linear:sandyloam	1705.405	100
B:boom:sand	1055.045	100
B:boom:sandyloam	530.975	100
B:linear:sand	1072.400	100
B:linear:sandyloam	544.360	100
C:boom:sand	747.155	100
C:boom:sandyloam	951.975	100
C:linear:sand	806.315	100
C:linear:sandyloam	1083.905	100
D:boom:sand	1379.840	100
D:boom:sandyloam	1115.085	100
D:linear:sand	1484.670	100
D:linear:sandyloam	1239.485	100
E:boom:sand	239.615	100
E:boom:sandyloam	120.630	100
E:linear:sand	293.485	100
E:linear:sandyloam	148.290	100

t-Student: 1.961163
Alpha : 0.05
LSD : 43.99186

Means with the same letter are not significantly different

Groups, Treatments and mean of the ranks

a	A:boom:sand	1901
a	A:linear:sand	1900
b	A:linear:sandyloam	1705
b	A:boom:sandyloam	1690
c	D:linear:sand	1485
d	D:boom:sand	1380

e	D:linear:sandyloam	1239
f	D:boom:sandyloam	1115
fg	C:linear:sandyloam	1084
fg	B:linear:sand	1072
g	B:boom:sand	1055
h	C:boom:sandyloam	952
i	C:linear:sand	806.3
j	C:boom:sand	747.2
k	B:linear:sandyloam	544.4
k	B:boom:sandyloam	531
l	E:linear:sand	293.5
m	E:boom:sand	239.6
n	E:linear:sandyloam	148.3
n	E:boom:sandyloam	120.6