Developing an intelligent overhead irrigation system for high quality horticultural field crops

HL0196 Final Report

September 2014

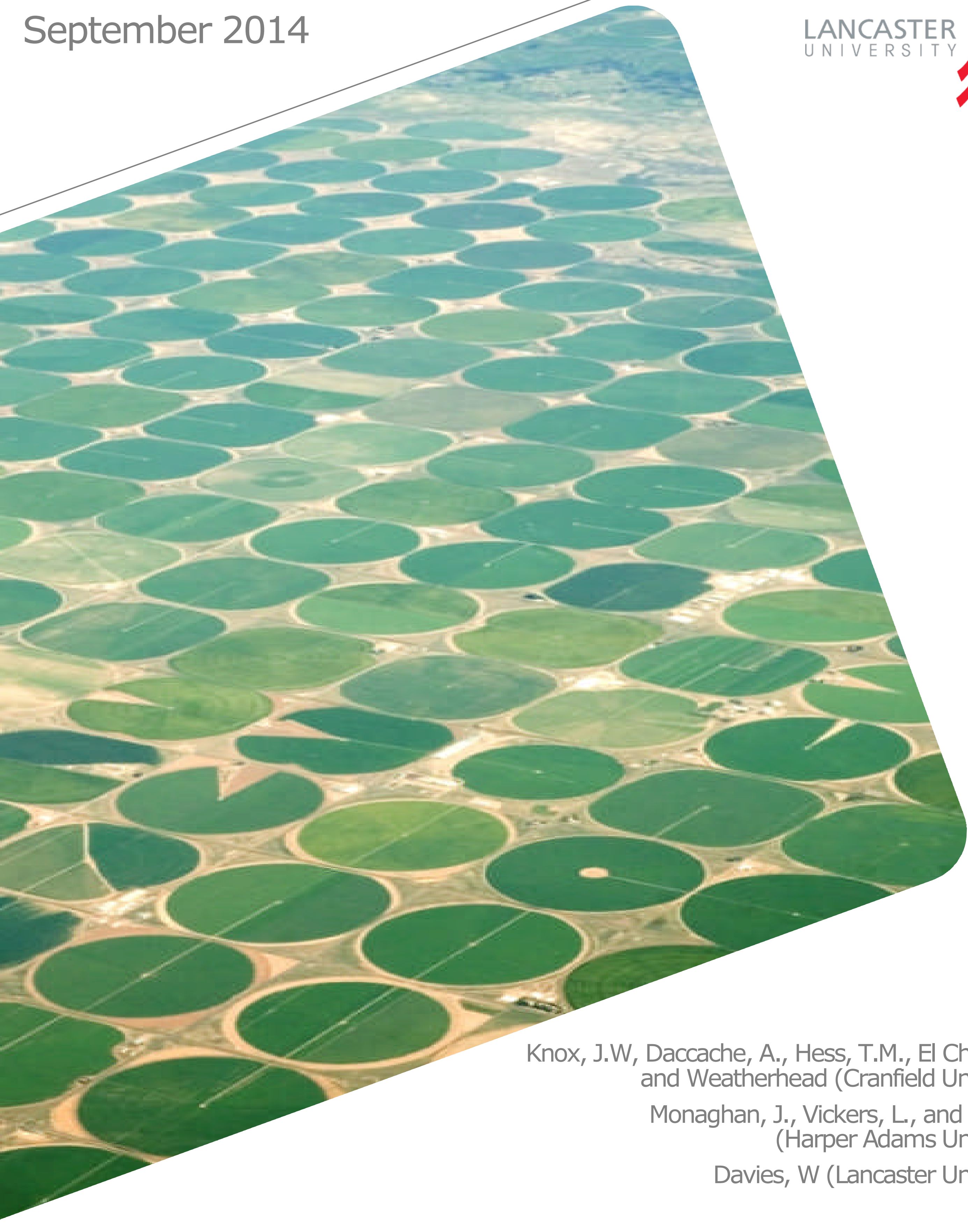

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Table of Contents

Executive Summary

Context

Notwithstanding inherent crop, soil and agroclimate variability and engineering constraints, conventional irrigation management aims to apply water in a uniform manner, minimising the negative impacts of non-uniformity on crop growth and productivity. In contrast, precision irrigation (PI) involves the 'differential' application of water. Scientists have defined PI variously in terms of (i) applying water in the right place with the right amount, (ii) the accurate and precise application of water to meet specific requirements of individual plants or management units to minimize adverse environmental impact or (iii) the application of water to a given site and timing to support optimum crop production, profitability or some other management objective.

Precision irrigation thus offers scope to save water, improve yield and support the sustainable intensification of crop production. However, reducing energy use and the environmental impacts of irrigation abstraction, particularly in catchments or regions where irrigation demand is concentrated and where water resources are scarce, are also becoming important 'drivers for change'. For farming businesses involved in high-value crop production, where quality assurance is a major determinant of profitability, PI also offers potential to reduce crop variability and improve post-harvest quality.

In this project we adopted a definition of precision irrigation proposed by Smith and Baillie (2009). Here PI was viewed as a 'concept' rather than a specific technique, and one that differs substantially from current practice. This concept represents a more holistic and adaptive approach to irrigation water management, rather than relating to only one method of application. It also attempts to integrate the factors influencing crop, soil and water management more closely with those that impact on irrigation engineering and hydraulic performance.

Project aim and objectives

The overall project aim was to evaluate precision irrigation technologies to reduce water and energy consumption and improve productivity in UK horticultural cropping. Four objectives were defined:

1. To evaluate wireless soil moisture sensing for monitoring spatial variabilities in soil water status and its suitability for precision irrigation scheduling;
2. To understand how soil moisture variability relates to variability in crop water status and how sensitive target crops are to deficit irrigation stress during crop development;
3. To engineer and test the concept of variable rate irrigation (VRI) on two overhead irrigation systems (a hose-reel fitted with a boom and fixed set sprinklers), and;
4. To combine the new knowledge on soil and crop management and hydraulic engineering under PI to evaluate how an intelligent irrigation management system could improve water and energy efficiency and crop productivity (yield and quality).

The research linked fundamental components of soil, plant and engineering science to develop new applied approaches to understand better how precision irrigation could be developed and implemented in a humid climate. The approaches were specific to supplemental irrigation on high-value field-scale horticultural crops, using onions and lettuce as representative crop sectors.

For each objective defined above, this report provides a chapter describing the research methods that were developed, the data collection and fieldwork, and the key findings and implications arising from the research.

A summary of the key findings relating to each objective are given below.

Key findings

To evaluate wireless soil moisture sensing for monitoring spatial variabilities in soil water status and its suitability for precision irrigation scheduling (see Chapter 3).

This objective involved two tasks, namely (i) conducting a detailed international literature review of wireless soil moisture sensor technologies for field-scale horticulture, and (ii) installing and evaluating performance of a wireless soil moisture sensor array installed on grower field sites over 3 growing seasons, to assess its suitability to support irrigation scheduling. The review included an assessment of the technical, agronomic and economic aspects of wireless sensor control drawing on published evidence from the US, Australia, New Zealand and Europe. The review confirmed that whilst a number of different types of wireless soil moisture sensing systems had recently emerged in the market (with some that had been evaluated) there still remained a noticeable lack of research and farmer guidance on the number of sensors required to provide optimal field coverage and to inform sensor placement. The second task attempted to investigate these aspects.

Over three years, a wireless soil moisture sensing array was installed for the growing season in lettuce and onion fields at each of the grower sites involved in the project. One of the challenges in sensor placement is in understanding the extent of spatial soil variability that actually exists within a field; from this, informed decisions can be made to decide on where to install the sensor. For this, a technique known as Electromagnetic Induction (EMI) was comprehensively tested and evaluated. Although EMI is not a new technology and has been used in precision agriculture for many years, its use in the UK seems to have rapidly developed. There are, however, practical and scientific challenges in using EMI to understand objectively how variable the soil is in a field. Whilst EMI was found to provide a useful visual indication of variability (which needs careful interpretation) scanned measurements must be combined with additional in-field soil sampling and laboratory analysis. This enables the measured apparent electrical conductivity (ECa) data to be used for mapping spatial variations in soil moisture, texture, organic matter content or compaction. Research then focussed on how to use the EMI data to delineate Irrigation Management Zones (IMZ).

Figure 1 *Combining EMI scanning with soil analysis and pedo-transfer functions to derive Irrigation Management Zones (IMZ).*

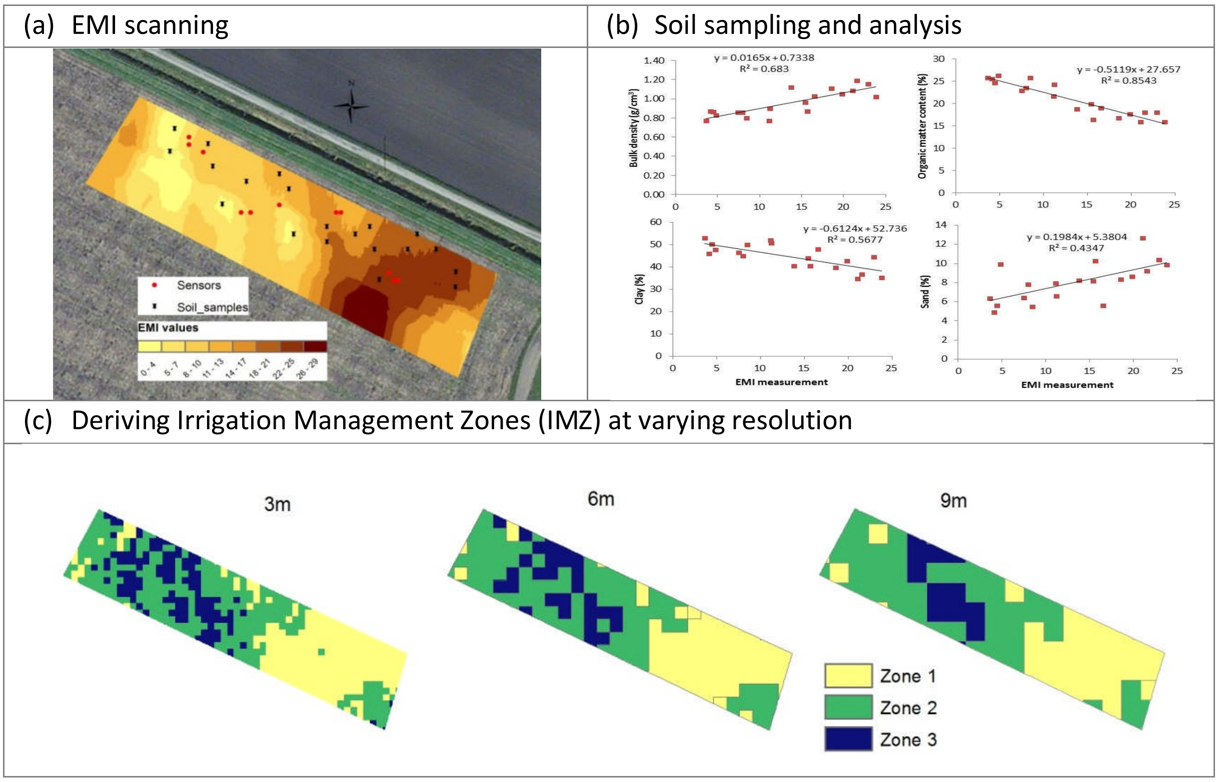


Figure 1 shows how IMZs can be delineated based on EMI scanning (Figure 1a), in combination with soil sampling and pedo-transfer functions (Figure 1b). However, the raw data must be aggregated into larger contiguous zones; these need to be large enough to be managed separately, yet small enough to minimize the soil variability within them (Figure 1c). This illustrates the importance of selecting the appropriate management scale for delineating IMZs and how these can then impact on field and water application variability.

For PI in a humid climate, the risk is in defining zones that are too small to cope with overlapping sprinklers, resulting in high variation in the scheduled application depth, and 'edge effects' of many small units located within a larger homogenous IMZ. Rather than varying the application rate in each IMZ, an alternative would be to modify the irrigation interval or timing. In the UK farmers generally consider the crop risks associated with under-irrigation to be much higher than over-irrigation. At present, the relatively low marginal cost of water applied would be sufficient to discourage growers to save water via PI; other indirect benefits such as reduced variability in crop quality and reduced environmental impact would more likely convince growers of the benefits of PI. Finally, irrigation schedules are constrained by the operating characteristics of hose-reel boom system, with the whole run being irrigated on a specific day. This can limit the benefits from PI, since schedules cannot be optimised for each IMZ without further development to incorporate feedback from in-situ soil moisture monitoring. The number and location of soil moisture sensors needed to monitor the temporal variation in soil moisture content, and hence determine PI schedules, would also depend on the number of the IMZ needed for each field.

In this project, EMI scanning was therefore found to be a fast, non-invasive and economic option for helping growers to delineate their IMZs and inform the siting of soil moisture sensors (and inform other in-field crop husbandry activities), particularly on variable soils; but the technique is limited in terms of its ability to explain the variability (texture, bulk density, moisture content, organic content) unless complemented by a systematic approach to soil sampling. Using EMI scanning to directly infer IMZs or other management zones is not recommended. The challenges in defining IMZ based on EMI for irrigation sensor placement under precision irrigation are described by Daccache *et al* (2014).

Daccache, A, Knox, J.W., Weatherhead, E.K., Daneshkhah, A, and Hess, T.M. (2014). Implementing precision irrigation in a humid climate: recent experiences and on-going challenges *Agricultural Water Management* Doi: 10.1016/j.agwat.2014.05.018.

To understand how soil moisture variability relates to variability in crop water status and how sensitive target crops are to deficit irrigation stress during crop development (see Chapter 4)

The rationale of this objective was to integrate measures of plant and soil water status over the development of a crop to inform irrigation schedules that will optimise crop yield and quality. The work package was split into three sub-objectives.

Understand how soil moisture variability relates to variability in crop water status (T2.1)

This work was undertaken at HAU and Lancaster University and guided subsequent experimental work. A critical value was established for lettuce 16% VVC (~500 kPa) and onion 15% VVC (~560 kPa) in glasshouse pot trials as the level at which plant growth responses were observed to diverge significantly from well watered plants. Subsequent physiology studies of lettuce and onion growth were undertaken in a polytunnel located next to the Crop and Environment Research Centre at HAU. Using 120 L containers half buried in the soil. Soil taken from the location of the polytunnel was amended with peat to give two defined uniform soils: 25% (high OM soil) or 5% (low OM soil) with which the bins were filled. Each bin had an access tube in the centre of the bin for a Diviner 2000 probe (Sentek Ltd) to monitor soil moisture to a depth of 70 cm.

Analysis of water loss/use through the profile of bin grown lettuce and onions showed that the top 30 cm (lettuce) and 40 cm (onion) (Figure 2) are the zones of significant water use and are the zones that should be monitored for accurate assessment of soil moisture availability in a managed soil.

Figure 2 *Accumulated weekly water loss (mm) from the profile (HortOnion01.*

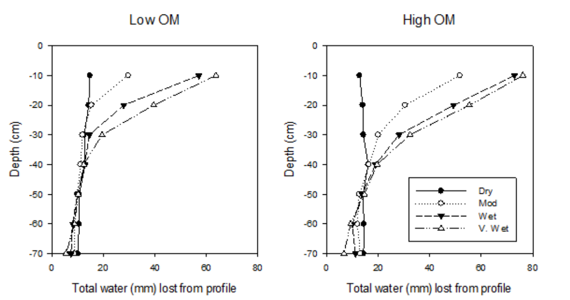
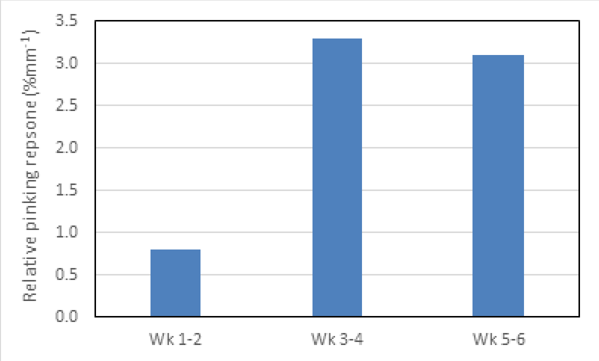


Figure 3 *Relative pinking responses for treatments where irrigation was withheld for two weeks starting at week 1, 3 and 5.*



Plants of both crops exposed to deficits accessed water progressively deeper in the profile. However, even low levels of irrigation led to water use in the top soil zone suggesting that this is the important area for functional water uptake.

Lettuce and onion plants were monitored during growth for a number of physiological parameters that are linked to water status, namely stomatal conductance, crop water stress index, relative water content, leaf number and leaf extension. No plant measure was consistently associated with soil moisture status. Direct measurement of soil moisture is still required to manage precision irrigation of field vegetable crops.

How sensitive are crops to deficit irrigation stress during crop development (T2.2)

By imposing deficit treatments at different timings in the bins we observed that lettuce was sensitive to irrigation deficit throughout crop growth but that the impact on yield was relatively less when imposed early in the crop. Onions were a more complex crop, having a longer growing season. We showed that imposing a deficit irrigation regime on onion will lead to a yield reduction through leaf loss and/or reduced leaf growth in early deficits or reduced bulb expansion in late deficits. Overall it was concluded that variable irrigation strategies should aim to maintain SMD close to 0 mm for maximum yield for both lettuce and onions. However, quality can be influenced by irrigation and this was studied in more detail.

Impact of varying irrigation regime on crop yield and quality (T2.3)

The extent and timing of deficit treatment affected post-harvest pinking in lettuce. The absolute level of pinking after 20 days in well watered control plants differed between experiments but within each experiment pinking was lower in heads with lower MC% at harvest. The relationship between Accumulated Relative Deficit during treatment and Relative Pinking was described by the equation y = 0.016x2 - 2.416x + 99.669. This relationship suggests that the extent of pinking in lettuce 20 days after harvesting could be reduced by 50% through imposing of a deficit of 25mm. We showed that early deficits have little effect on pinking but mid and late growth deficits have similar potential to reduce pinking in a crop (Figure 3).

Onions are stored for up to 9 months commercially and cured onions were cold stored for 3 and 6 months before being destructively assessed. We observed no significant response of post-harvest quality to deficit imposed during growth but there was an Indication that deficit increases sprouting and reduces storability.

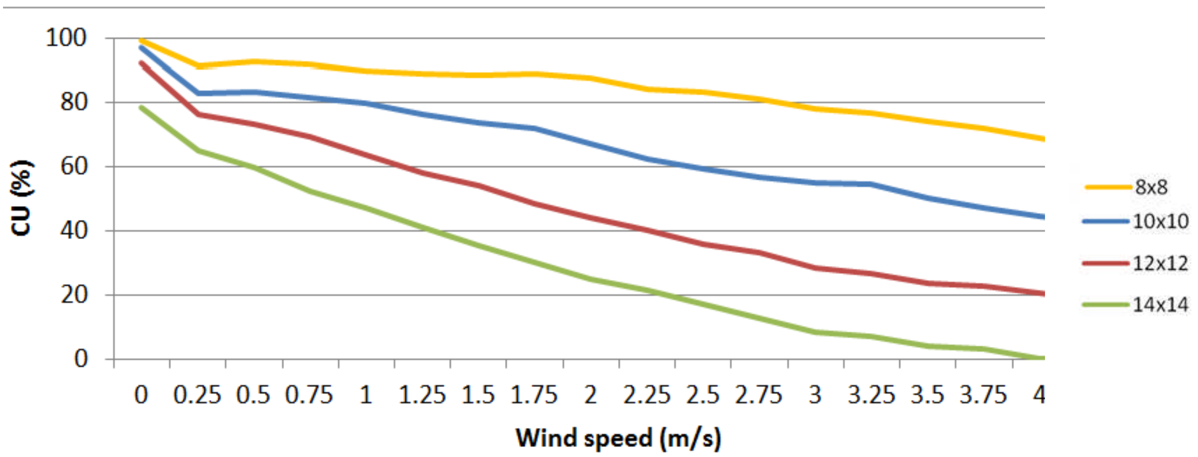
To engineer and test the concept of variable rate irrigation (VRI) on two overhead irrigation systems - a hose-reel fitted with a boom and fixed set sprinklers (see Chapter 5)

This task involved developing and testing two prototype irrigation technologies to assess whether more accurate, spatially variable irrigation application could be achieved through variable rate irrigation (VRI). These technologies could then be linked to information from planting records, soil maps and/or wireless soil moisture sensing arrays to improve water and energy efficiency. Optimisation of which sprinklers should operate simultaneously would allow for smaller pipe sizes and operating pressure, thus reducing capital and running (energy) costs on a fixed set sprinkler system. The research was conducted on an experimental field site at Cranfield University under controlled conditions, coupled with field data from grower sites to reflect typical operating conditions. These datasets were then combined and used to calibrate a ballistic model for spatially simulating irrigation distribution uniformity across a field under varying environmental and operating conditions, and for modelling impacts on crop yield (Objective 4).

The options for installing small hydraulic valves on each sprinkler head were first evaluated. A solid-set sprinkler irrigation rig was built on a level grass site at Cranfield University. Electronic valves were fitted to each sprinkler and powered using a 2-wire system with electronic decoders. The feasibility for using remote (wireless) control valves was investigated. Extensive field evaluations were conducted to assess how individual sprinkler control could be used to improve uniformity. The hydraulic performance under optimal (design pressure) and sub-optimal conditions (low and high pressure, high wind conditions) was evaluated. Extensive field data were collected for parameterising and calibrating a ballistic model for simulating overlapped water distribution uniformities, for a range of operating conditions. Following calibration, the model was used to assess the impacts of varying operating pressure, wind conditions (wind speed and direction) and system configuration (changing lateral and sprinkler spacing) on system performance and precipitation (application) rates. The approaches developed on the solid set sprinklers were similarly extended to a hose reel fitted with a boom and its performance similarly evaluated.

As an example, the observed effect of increasing wind speed on irrigation uniformity (CU) for different sprinkler spacing is shown in Figure 4. At high wind speeds and in order to maintain acceptable uniformity it is necessary to reduce the sprinkler spacing. However, this increases the volume of water applied and inevitably increases capital (pipe and sprinkler) costs. A balance needs to be struck between minimising wind effects and pressure on sprinkler performance, against the economic viability of a system capable of applying water variably with a high degree of control.

Figure 4 *Derived impact of wind speed (m/s) on application uniformity (CU%) for different sprinkler spacing (m) on a rectangular grid.*

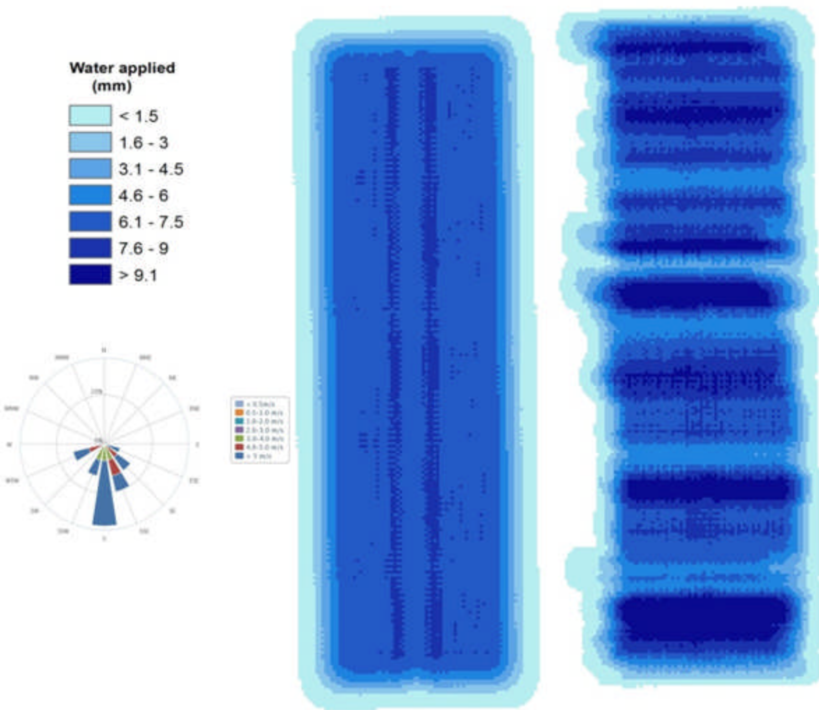


Further work is needed to develop suitable algorithm rules to optimise the switching (control) of sprinklers on/off in response to changing wind/pressure conditions and to operationalise the technology for grower use, but the prototype has been successfully developed and tested.

For the hose-reel with boom system, extensive field tests were similarly conducted with remote control valves fitted on the prototype to operate the individual sprinklers. Field data were collected for various sprinkler nozzle packages most commonly used on UK booms, under both 'no wind' and 'windy' conditions. These data were used to parameterise and calibrate a ballistic model developed in this project for a boom to simulate the overlapped water distribution uniformity under a moving boom for a range of operating conditions (i.e. changing wind speed and direction and operating pressure (optimal and sub-optimal) (Figure 5).

Figure 5 *Simulated water distribution pattern from an overhead irrigation system (hosereel fitted with a boom) operating under (a) no wind conditions, and (b) real-time wind conditions (wind rose highlights the wind speed frequency and direction).*

(a) (b)



The outputs from these simulations were also used as input for assessing the yield impacts associated with switching from conventional to precision irrigation (PI) (Objective 4). The approaches developed and the key outputs from this part of the project have resulted in two key high-impact papers:

- Knox, J.W., Weatherhead, E.K., Hess, T.M. and Daccache A. (2014). Integrating biophysical and ballistics models to assess agronomic and environmental impacts of precision irrigation on crop yield. *Environmental Modelling and Software* (accepted subject to revision);
- Perez-Ortola, M., Daccache, A., Hess, T.M., and Knox, J.W (2014). Simulating impacts of irrigation heterogeneity on onion (Allium cepa L.) yield in a humid climate. *Irrigation Science* Doi: 10.1007/s00271-014-0444-2.

The operational and technical challenges were also discussed at the end of project conference (UKIA Peterborough, March 2014) and field demonstration events.

To combine the new knowledge on soil and crop management and hydraulic engineering under PI to evaluate how an intelligent irrigation management system could improve water and energy efficiency and crop productivity (yield and quality).

For this final objective, the hypothesis was that a precision irrigation system capable of varying water application to match varying need, caused for example, by changes in soil or topography, or due to sequential crop production patterns, would deliver improvements in water and energy efficiency and crop productivity. By developing an improved understanding of the links between soil moisture and crop water status (Objective 2) and particularly the importance of spatial soil and water variability across an irrigated field (Objective 1 and 3) we attempted to quantify the impacts of irrigation heterogeneity on crop productivity (yield), and the economic viability of investment in precision irrigation. Using outputs from Objectives 1 to 3, Objective 4 focussed on two key tasks:

(i) To develop an integrated approach to combine knowledge of ballistics and biophysical crop response to assess the agronomic (yield) impacts of precision irrigation, and;

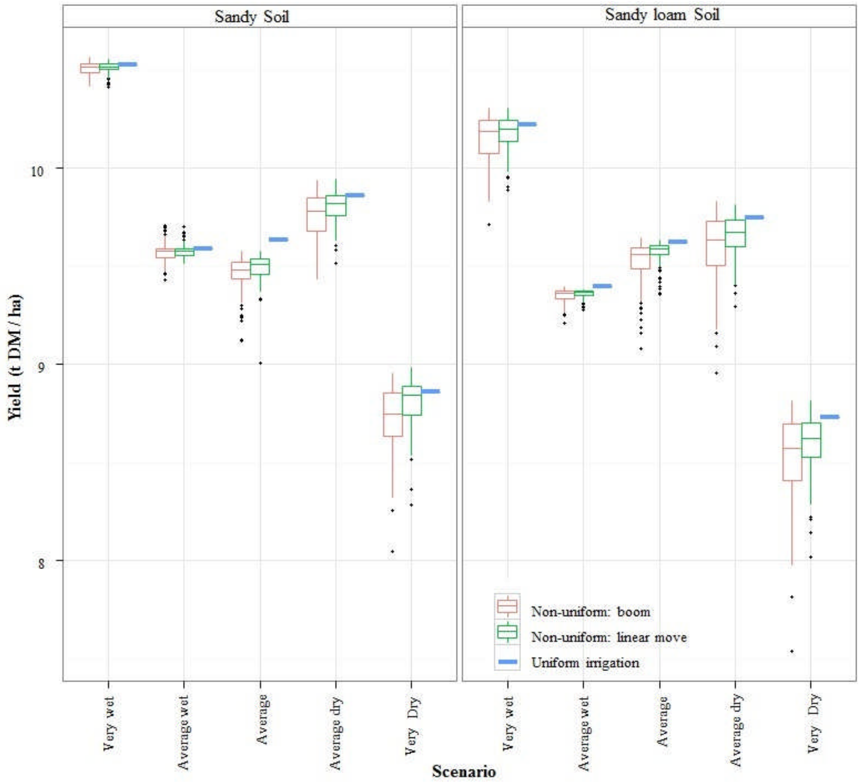
(ii) To undertake a financial impact appraisal to assess the economic viability (costs and benefits) of investment in precision irrigation technology and its sensitivity to key variables.

Both tasks used onions as a ‘representative’ crop for analysis with the approaches developed based on combining experimental and field data within an integrated modelling framework to allow for scenario and sensitivity analysis. A detailed explanation is given in Chapter 6 and the research published in the following high impact science journals (available on request):

- Perez-Ortola, M., Daccache, A., Hess, T.M., and Knox, J.W (2014). Simulating impacts of irrigation heterogeneity on onion (Allium cepa L.) yield in a humid climate. *Irrigation Science* Doi: 10.1007/s00271-014-0444-2.
- Perez-Ortola and Knox, J.W (2014). Water relations and irrigation requirements of onion (Allium Cepa L.): a review of yield and quality impacts. *Experimental Agriculture* Doi: 10.1017. S0014479714000234.
- Daccache, A, Knox, J.W., Weatherhead, E.K., Daneshkhah, A, and Hess, T.M. (2014). Implementing precision irrigation in a humid climate: recent experiences and on-going challenges *Agricultural Water Management* Doi: 10.1016/j.agwat.2014.05.018.
- Knox, J.W., Weatherhead, E.K., Hess, T.M., and Daccache, A (2014) Integrating biophysical and ballistic models to assess agronomic and environmental impacts of precision irrigation. *Environmental Modelling and Software*.
- El Chami D., Knox JW, Daccache A., and Weatherhead, EK (2014) Assessing environmental cost-benefits of precision irrigation using a travelling hose-reel irrigator with a boom in a humid climate – A study in the East of England. *Precision Agriculture* (submitted).

For the first task, a study combining experimental field data with biophysical crop modelling was completed to assess the impacts of irrigation heterogeneity on onion yield. The AquaCrop model was calibrated and validated for brown onion (*cv Arthur)* and used to simulate yield variability under a set of contrasting soil and agroclimatic conditions assuming perfect (100% uniform) irrigation. The impacts of non-uniform irrigation as measured on-farm (Elveden grower site) under two overhead systems (mobile hose reel fitted with boom and a linear move) were then evaluated using scenario analysis and multi-model runs. Stochastic modelling confirmed that the lowest yield occurs on the lowest moisture retentive soils under the driest agroclimatic conditions with non-uniform irrigation (Figure 6). There is much greater yield variability in dry years compared to wet years. In wet years, rainfall reduces the scheduled number of irrigation events and buffers the effects of irrigation non-uniformity on yield. Yields were more variable under the mobile hose reel system fitted with the boom compared to the fixed linear move system. The modelled yield variability under non-uniform was similar to the observed yields reported by growers based on an industry survey.

Figure 6 *Box and whisker plot showing Aquacrop simulated onion yield (t DM ha^{-1}) under 'uniform' and 'non-uniform' irrigation, using a hose reel with boom and a linear move, on a sandy and sandy loam soil, for different climate years (very wet, average wet, average, average dry, very dry).*



The study also highlighted the importance of achieving high irrigation uniformity in dry years on light soils to maximise yield (Figure 4) and provided the required data for evaluating the potential yield benefits that might accrue from precision irrigation (Task 2). The benefits of precision irrigation (PI) will of course be site and crop specific and depend on a range of factors such as the magnitude of soil variability within the field, local agroclimate conditions, the method of irrigation and cost of water (particularly if storage is required). The final part of the project therefore involved undertaking a financial impact appraisal to assess the economic viability (costs and benefit) of investment in precision irrigation technology and its sensitivity to key variables.

For the economic assessment, the project integrated modelling tools to simulate the benefits of precision irrigation (PI) and conventional irrigation (CI) and compare against rainfed production, for an onion crop grown in a typical humid climate in Eastern England using a hose-reel fitted with a boom. The Aquacrop model was used to simulate irrigation water requirements (IWR) and corresponding yields on three different soil types (sand, sandy loam and loamy sand). We considered three IMZ in the field (not optimised) and weighted the IWR and yield with the corresponding percentage areas. Overall, although the precision irrigation system modelled led to significant water savings and energy efficiency benefits, these alone do not cover the additional costs. However, crop yield or quality benefits, higher water costs (or values) and/or greater soil variability would make investment in precision irrigation more viable. Optimisation of precision irrigation system management could also lead to significant improvements.

The potential economic benefits from PI for supplemental irrigation on field-scale crops in a humid climate such as England appear modest. The benefit to the grower in the reduced cost of water and energy is estimated to be typically less than £25 per hectare that is over-irrigated. Clearly the development and uptake of PI would need to be justified more in terms of the wider benefits to crop quality (reducing variability in crop samples) and the reduced environmental impacts associated with irrigation (reduced drainage and higher nitrogen use efficiency). Further work is however required to assess these under real situations and to provide quantitative evidence to substantiate preliminary evidence regarding the agronomic (yield) benefits of precision irrigation.

Science and industry benefits

This project provided multiple opportunities for research outputs to flow between the academic and industry partners. The key activities that have supported knowledge transfer have included technical meetings, on-farm demonstration/field visits, farmer workshops, training events, publishing an information booklet and articles in the industry press, and organising a major industry conference. These have provided excellent opportunities for presenting the key findings from the research, demonstrating technical developments and their in-field application, publishing information to highlight new research, developments and grower options, promoting research through trade and industry media and sharing knowledge through the end of project conference.

The beneficiaries have included growers and businesses involved in the Hortlink project, other growers, companies, farmer organisations, crop sector organisations (e.g. BCGA, BLSA), the water regulatory authority (EA), UK levy boards (AHDB HDC and PCL) and stakeholders with interests in food production, water and environmental management (e.g. retailers). In addition to the industry knowledge transfer, a number of contributions into high impact science journals have been generated (highlighted above). In addition to science papers, the following industry publication was also produced, and available for download from: http://www.ukia.org/irrigationbooklets

Knox, J.W., Daccache, A., Hess, T.M, and Weatherhead, E.K. (2014) *Precision Irrigation: assessing the technical, agronomic and engineering challenges for UK field-scale agriculture and horticulture*. An Information Booklet for growers, Cranfield University.

Acknowledgement

This project (Hl0196) was funded by Defra under their Hortlink programme. It was also supported by the following industry organisations and individuals, who provided significant inputs into the project. Their contributions are all gratefully acknowledged.

- Dr Ed Moorhouse (Industry lead), Will Forbes, Dr Emma Garrod and field staff at Gs (Ely);
- Andre Francis, Ian Robertson and field staff at Elveden Estate (Norfolk);
- Dermot Tobin and field staff at PDM Produce UK Ltd (Shropshire);
- Adrian Colwill, Warren Briggs and Darren Hall (Briggs Irrigation);
- Anthony Hopkins and staff at Wroot Water;
- Dr Bernhard Pacher (Adcon Telemetry);
- David and James Martin at Plantsystems;
- Dr Tim Lacey and Tom Will (VCS Ltd, Norfolk);
- Melvyn Kay and members of the UK Irrigation Association (UKIA);
- Cheryl Brewster and staff at the HDC, and;
- Dr David Cole and project staff at Defra

1. Research context

1.1 Commercial and technical background

Irrigation of field vegetables has changed relatively little over the last 3 decades, but rising energy costs and supermarket demands for premium quality produce are forcing growers to address the impacts of irrigation heterogeneity (non-uniformity) on crop quality whilst simultaneously reducing energy and water consumption. This is not just a UK issue (Morison *et al*., 2007), but an international priority (Molden, 2007). Field vegetables are the most important crop in the UK after potatoes in terms of irrigated area and crop value (Weatherhead, 2007). Nearly three-quarters are irrigated using overhead methods which are inefficient in energy and water use. Whilst drip irrigation can improve water efficiency and crop quality in some sectors (HL0165) it is not the solution for field-scale horticulture, where sequential plantings and rotational cropping are better suited to portable overhead systems. Water regulation is also impacting on production, with water availability and reliability likely to become major constraints on horticultural businesses. Growers will have to demonstrate efficient and sustainable use of water to renew their abstraction licences and comply with supermarket grower protocols. Developing innovative approaches to combine knowledge of soil, crop and equipment management practices to reduce the variability in crop quality through precision irrigation is an industry priority.

1.2 Problem/opportunity

Making maximum use of soil moisture and rainfall, knowing precisely where and when irrigation has to be applied, and then applying it accurately and uniformly, are the fundamental steps in the 'pathway to water efficiency' (Knox *et al*., 2006). Irrigation is already an essential component in horticultural production to maximise yields, but there is growing evidence that optimised irrigation regimes also lead to improved post-harvest product quality leading to reduced crop waste through the supply chain. However, growers are currently restricted in their ability to match the timing and frequency of irrigation applications to spatial and temporal variations in soil moisture and crop growth. They generally have only limited information on plant water status, rely on limited point measurements of soil as a proxy for field scale soil moisture availability; and use irrigation systems that lack the flexibility and control for variable water application. Recent developments in soil sensors, wireless telemetry and application equipment provide a timely opportunity to develop a closed-loop system capable of applying water variably across field crops on overhead irrigation systems. In addition, new techniques that rapidly measure plant water status and improved soil moisture sensing technology will allow irrigation to be scheduled from plant responses rather than solely soil water availability. The combination of using irrigation trigger points at defined physiological set points combined with a precision application system will enable significant water savings in field-scale horticultural production, with an associated reduction in nutrient leaching and energy used for pumping.

1.3 Scientific background

Vellidis *et al.* (2008) developed a prototype real time soil sensor for scheduling irrigation on cotton under arid conditions in the USA. This research will develop an equivalent wireless soil moisture sensor array for scheduling irrigation on lettuce and onions grown under supplemental rainfall conditions. HL0165 showed that precision application of water (using drip tape) could save up to 60% of water and that reduced irrigation regimes could improve post-harvest quality of lettuce crops. However, although drip irrigation can be managed with a high degree of control, it cannot apply water variably (emitters are designed to provide uniform discharge). Overhead systems are more suited to variable rate application. In HLO168, an approach to scheduling irrigation was developed where water was applied to mitigate plant stress (assessed by perturbed stomatal behaviour). The variability in irrigation application and its impacts on crop yield and quality has been modelled by

Lacey (2007), and a prototype precision irrigation system using Bluetooth technology has been developed to provide variable applications on arable crops under centre pivots (Kim *et al*., 2007). This research will develop equivalent technologies for UK conditions where growers use portable overhead booms and sprinklers.

The aim is to develop an intelligent irrigation management system which integrates soil moisture sensing, wireless communication and variable delivery technology, to improve crop quality and reduce water consumption and other environmental impacts. We will use small-scale instrumented university experimental sites to test a real time wireless soil moisture sensor array, and evaluate the role of plant water status measurement techniques (including thermal imaging) for monitoring varying levels of crop water stress, using lettuces and onions as reference crops. The crop measurements will be used to calibrate the soil moisture sensor readings to define trigger irrigation points. Technologies for applying water variably from booms and sprinklers will be developed and tested. The soil sensing, crop monitoring and variable application technologies will be coupled to form a 'closed loop system' which will be evaluated under contrasting crop, soil and agroclimatic conditions at two grower sites. This will include an assessment of system performance, practicality (ease of management), impacts on yield and post-harvest quality, and economic appraisal. The fieldwork will inform decisions regarding technology transfer to other horticultural crops.

2. Project aim and objectives

The overall aim was to develop precision irrigation technologies to reduce water and energy consumption and improve post-harvest quality of high value horticultural crops. The project had 4 science objectives:

1. To test a real time wireless sensor system for monitoring the spatial distribution of soil water status in field-scale vegetable production;
2. To evaluate crop sensing technology for estimating soil water and plant water status in field-scale vegetable production;
3. To engineer and test a control system for variable irrigation water application, and;
4. To combine the new technologies into an intelligent irrigation management system, and evaluate its' potential to improve water efficiency and crop quality.

The research interlinks three key areas of research and development, focusing on the most important aspects of soil, plant and engineering science that impact on water and energy efficiency and crop quality in field-scale horticulture. For each objectives, the following chapters summarise the research methods developed, the fieldwork undertaken, the results obtained and the key findings and implications.

3. Primary and secondary milestones

In addition to four science objectives (Chapter 2) primary and secondary milestones were defined (Table 1). Achievement of these was essential if the overall project objectives were to be met.

Table 1 *Primary and secondary milestones (primary milestones shaded).*

MS	Description	Month	Status
-	Complete IP agreement between partners	3	Completed
P1.1	Define sensor and communication technologies for development of wireless soil moisture sensor array	3	Completed
S1.1	Complete literature review of soil variability and irrigation, soil sensors, wireless networks and comms technologies	4	Completed
P1	Complete 1st year progress report	6	Completed
S2.1	Establish trial plots with lettuce and onion, install irrigation and sensors	7	Completed
P1.2	Complete development of prototype wireless soil moisture sensor array	8	Completed
S1.2	Install prototype array in experimental field plots	8	Completed
A1	Complete Annual Report (Yr1)	12	Completed
P1.3	Complete field evaluation of wireless soil moisture sensor array under controlled conditions	16	Completed
P2.1	Complete assessment and correlation of soil moisture variability with variability in crop water status	17	Completed
S3.1	Construct prototype solid set sprinkler rig and control system	22	Completed
S3.2	Complete prototype variable rate boom and control system	24	Completed
A2	Complete Annual Report (Yr2)	24	Completed
S2.3	Complete deficit irrigation trials on lettuce and onion crop water stress	25	Completed
P3.1	Complete development and evaluation of prototype for individually-valved solid set sprinklers and control system	27	Completed
S2.5	Complete assessment of relationship between stomatal conductance and leaf growth with plant-soil water status	28	Completed
P3	Complete 3rd year progress report	30	Completed
P2.2	Complete assessment of sensitivity to deficit irrigation stress during crop development	36	Completed
A3	Complete Annual Report (Yr3)	36	Completed
S2.6	Complete post-harvest shelf life trials	37	Completed
P4.2	Complete evaluation of prototype closed loop system under bare soil (experimental) conditions	40	Completed
P3.2	Complete development and evaluation of prototype for variable rate boom application and control system	41	Revised and Completed
S4.1	Install prototype closed loop system at grower field sites	42	Completed
S4.2	Install prototype closed loop system at two grower field sites	42	Completed
P4	Complete 4th year progress report	42	Completed
P4.1	Prototype closed loop system, integrating wireless soil moisture sensing array with variable rate application technology	43	Revised and Completed
S4.3	Complete field evaluations of closed loop system under sprinklers and boom irrigation	48	Completed
P2.3	Complete assessment of varying irrigation regime on crop yield and quality	49	Revised and Completed
S4.4	Complete irrigation cost-benefit study of closed loop system	49	Completed
P4.3	Complete evaluation of closed loop system using variable rate boom, including economic assessment	50	Completed
A4	Complete Final Report	52	Completed

The following changes in the timing and completion of four Primary Milestones for Year 3 and 4 were proposed and agreed within the project. Due to delays in project start (planned for Sept 2009, actual March 2010), two primary milestones for Objective 2 both ended mid-season. It was therefore agreed that milestones P2.2 and P2.3 be shifted forward to match growing seasons; from July 2012 (Month 29) to Feb 2013 (Month 36) and from June 2013 (Month 40) to March 2014 (Month 49), respectively. Secondary milestones were similarly adjusted to match the growing season. No changes in the research conducted were proposed. It was also agreed to move Milestone 4.1 to incorporate data from the third year of polytunnel trials at HAUC. No other changes in research under this objective were required.

Excessively wet summer conditions during 2012 also hampered fieldwork, notably the development and testing of the prototype variable rate boom (P3.2). The development and testing of the fixed sprinkler system was not impacted as fieldwork started earlier between Feb-June 2012 (P3.1). It was agreed that the completion date for the boom be changed from Sept 2012 (Month 31) to July 2013 (Month 41). No other changes in research under this objective are required.

The research undertaken to address each of the primary milestones has led to a number key science outputs and industry dissemination activities. See Executive Summary and Chapter 8 for details.

4. Assessing wireless soil moisture monitoring technology (Objective 1)

4.1 Hypothesis and approach

For this objective, the hypothesis was that an improved understanding of spatial and temporal variabilities in soil moisture that exist in irrigated fields using wireless soil sensor arrays could provide improved information for growers to develop irrigation schedules to maximise crop quality.

Temporal changes in soil water status can be measured in many ways, ranging from tensiometers through to time domain reflectrometry (TDR). These variously give a single point moisture reading or a vertical profile of moisture readings but instrument costs and manpower implications (labour availability and cost) have often limited the ability to sample multiple points repeatedly and at high spatial resolution. Their accuracy for monitoring soil moisture and suitability for irrigation scheduling has also been previously evaluated (Stalham *et al*., 1999). The rationale in this work was therefore to identify how best to use commercially available sensors in a semi-permanent installation to understand the spatial and temporal variability that exists in soil water status across a field, and then assess how these sensors could support irrigation scheduling. The approach involved a combination of literature review, followed by soil moisture sensor installation and monitoring in field sites at each farm involved in the project, including lettuces at Gs (Ely, Camb) and PDM (Shropshire) and on onions at Elveden (Norfolk). A preliminary assessment of the technologies available for growers and their current approaches to soil moisture monitoring was conducted in Year 1; subsequent more detailed sensor evaluations were then conducted on-farm in years 2 and 3. The objective involved two tasks:

1. Review and assess wireless soil moisture sensor technologies for field-scale horticulture, and;
2. Install and evaluate performance of a wireless soil moisture sensor array to assess suitability to inform irrigation scheduling in field-scale horticulture.

4.2 Review soil moisture sensor and wireless technologies

This task involved a detailed review of published international science (peer review) and grey (industry) literature on the development and application of wireless soil moisture sensor arrays for agriculture and horticulture. The review findings were discussed in the first Annual Report (AR1) and as a separate technical annex (Abriqueta, 2011). Readers interested in an overview of the methods available to measure soil moisture are referred to Hilton *et al* (2010). The review assessed the technical, agronomic and economic aspects including use of wireless sensors under contrasting soil and agroclimatic conditions, on different crops and under contrasting irrigation systems. Project researchers also attended an international symposium on soil water measurement using capacitance, impedance and time domain transmission in Murcia (Spain) in 2010.

4.3 Field test wireless soil moisture sensor array

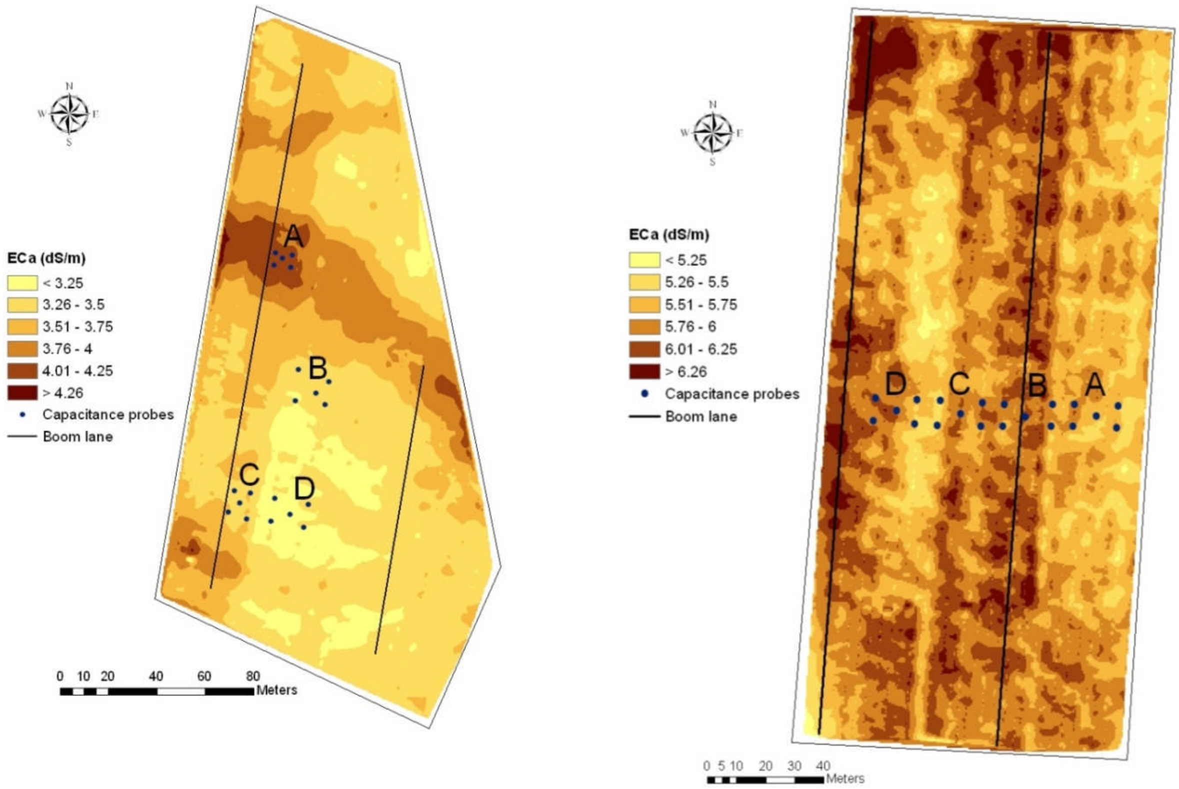
Although soil physical properties are heterogeneous, their impact on soil water relations is less. For example, the variability in available water capacity is less than the variability in, for example, sand fraction, and the impact on plant growth can be attenuated. Perhaps of greater significance is the variability in physical restrictions on root growth due to localised shallow bedrock or the presence of compacted layers (plough pans). These issues were explored through a series of extensive field tests between 2011 and 2013 whereby fields with conditions such as undulating terrain, compacted layers and shallow subsoil were instrumented and then monitored to assess the robustness of the soil sensor arrays in dealing with heterogeneous soils and the quality of the data provided.

A detailed description of the approaches developed for tasks T1.2 and 1.3 are given in Annual Reports AR2 and AR3. The key findings are summarised below.

- Field observation studies on lettuces (G's and PDM) and onions (Elveden) over three consecutive years provided highly valuable insights into crop and soil management practices, irrigation management challenges and the magnitude and scale of variability growers have to contend with in optimising production (yield and quality) in field-scale horticulture;
- A technique known as Electromagnetic Induction (EMI) was comprehensively tested and found to provide a useful technique for mapping soil variability, and for understanding the magnitude and scale of variability in-field. EMI provides a useful visual indication of variability (Figure 7) but measurements must be combined with soil sampling and laboratory analysis if the measured apparent electrical conductivity (ECa) is to be used as surrogate for soil moisture, texture, organic matter content or compaction;

Figure 7 *Location of soil moisture monitoring blocks (A, B, C and D) at G's (a) and Elveden (b) in 2010.*

(a) G's field site (Cambs) (b) Elveden Estate (Suffolk)



- At one site (Ely), a good positive correlation was observed between EMI values and soil bulk density and a negative correlation between EMI and organic matter content. The correlations were weaker for samples with high clay and sand fractions. However, the EMI value is determined by a combination of different factors including organic content, compaction, soil texture, water content and temperature. As soil scanning has been made for that specific site when the field ground conditions were dry, the impact of water content on the EMI values was minor across the field.

- EMI scanning was found to be a fast, non-invasive and economic option for helping to delineate irrigation management zones and to support optimal siting of wireless soil moisture sensors, particularly on variable soils, but the technique is limited in terms of its ability to explain the reasons for soil variability (texture, bulk density, moisture content, organic content;

- The wireless soil moisture sensor arrays were installed in each field and provided useful real-time (15 min interval) data on soil moisture content, and its variability over time with depth. The wireless soil moisture technology proved to be solid and highly reliable if well maintained at the beginning of each season (Figure 8). However for better use of the measured data, it is recommended that soil moisture sensors be carefully calibrated for each field soil type.

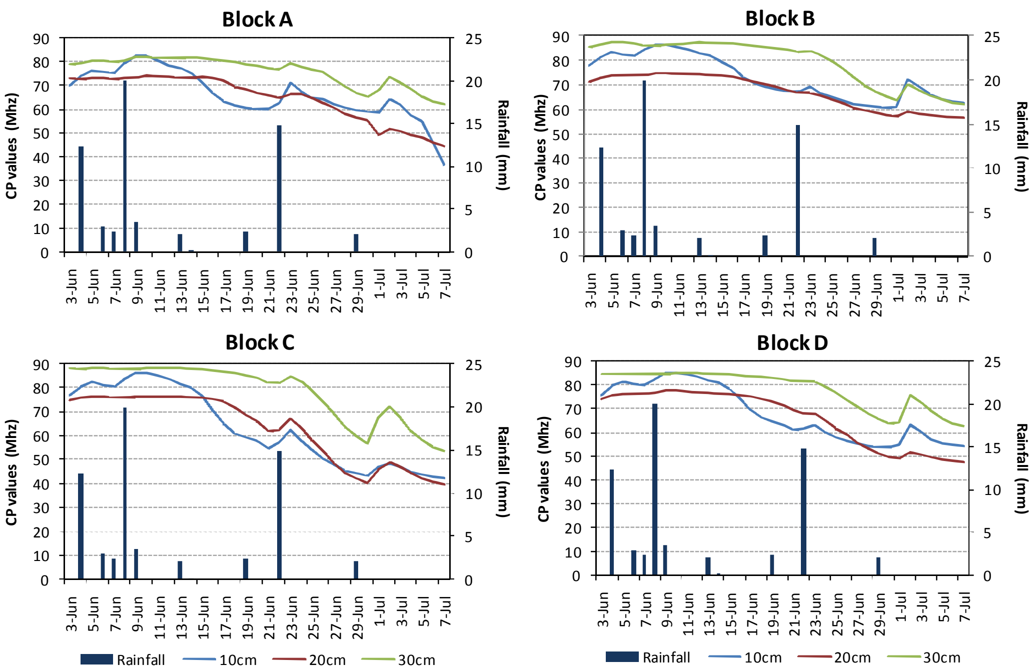
Figure 8 Wireless soil moisture sensors installed in lettuces at G's field site in 2010.

(a) Rain gauge, data transmitter and solar panel

(b) Adcon capacitance probe connected to datahub

- The field evaluations highlighted much greater range in soil moisture variability on the Fenland soils compared to Breckland soils, due to the presence of old alluvial clay deposits (roddens) (Figure 7a). However, on these soils, expected correlations between soil moisture and soil variability derived from EMI scanning were not observed (Figure 9). Instead soil moisture was found to be more variable within each block (A, B, C, D) than between different blocks. These variations are likely to be caused by a number factors including sensor instrument siting, installation (soil contact, compacted layers, stones), local dry spots, soil compaction, soil cracking around the sensors and/or tensiometers and non-uniform water application. For example a void around the sensor is likely to over-estimate readings at soil saturation and under-estimate readings when drained.

Figure 9 *Example data showing from wireless arrays showing average capacitance probe values for each block (A, B, C and D shown in Figure 1a) and for each soil depth in the lettuce field in 2010.*



5. Crop sensing to estimate soil and plant water status (Objective 2)

5.1 Hypothesis and approach

Direct measurement of crop water status can be used to calibrate moisture sensors and thus help vary water application according to crop need. Stomatal conductance, plant water status, relative growth rates and thermal imaging can all be used as measures of transient stress directly in the plant. Such measures may be effective ways of scheduling irrigation but this hypothesis is largely untested, particularly since some crops can effectively regulate shoot water status as soil dries. Others lose control of leaf water status because stomata are insensitive to soil drying. Two different crops can show these different combinations of plant variables at equivalent soil water potentials. Hence the acceptable level of plant/soil water stress for optimum irrigation scheduling is difficult to define without more fundamental monitoring of plant soil relationships of different crops in different field situations.

In HL0168, an approach to scheduling irrigation was taken where water was applied to mitigate plant stress (assessed by perturbed stomatal behaviour). This approach proved highly successful but more work was needed with different crops to determine the amount of water required to alleviate stress. It is known that irrigation requirements (volume and frequency) vary depending on crop growth stages and can directly affect key crop quality criteria. Existing irrigation guidelines were developed for traditional overhead irrigation methods (rain gun) based on large applications, but optimum schedules are likely to be quite different particularly when using modern irrigation systems which apply water more uniformly and with greater flexibility in application rate (“little and often”). In addition, schedules were originally defined to maximise yield; modern schedules need to consider impacts of plant stress on crop quality and human nutritive value. The rationale of this objective was therefore to integrate measures of plant and soil water status over the development of a crop into irrigation schedules that will optimise crop yield and quality. This will help improve our understanding of crop water requirements and how they can be estimated from measurements of plant and soil variables undertaken cheaply and quickly in-field.

5.2 Experimental trials

This section refers to crop physiology trials conducted at HAU; field trials at Elveden, G’s and PDM are covered elsewhere. This section presents the results from the experimental trials at HAU, and highlights the key findings and implications. All experiments have previously been reported in the Annual Reports (AR2, AR3, AR4). Table 2 summarises the experimental programme at HAU and Lancaster University in Years 2 to 4. The experiment titles have been used in the Annual Reports.

Table 2 *Summary of experimental trials conducted at HAU.*

Experiment	Year	Location	Crop	Obj. 1	Obj. 2	Obj. 3	Varying deficit	Timing of deficit
Hortlett01	2	Polytunnel	Lettuce	✓	✓	✓	✓	
Hortlett02	2	Polytunnel	Lettuce	✓	✓	✓	✓	
Hortlett04	3	Polytunnel	Lettuce		✓	✓		✓
Hortlett05	3	Polytunnel	Lettuce		✓	✓		✓
Hortlett06	4	Polytunnel	Lettuce		✓	✓		✓
Hortlett07	4	Polytunnel	Lettuce		✓	✓		✓
HortRhizo01	2	Glasshouse	Lettuce	✓			✓	
HortGH01	2	Glasshouse[a]	Lettuce	✓			✓	
Hortonion01	2	Polytunnel	Onion	✓	✓	✓	✓	
Hortonion02	3	Polytunnel	Onion		✓	✓		✓

Hortonion03	4	Polytunnel	Onion		✓	(✓)[b]		✓
HortGH02	4	Glasshouse	Onion	✓			✓	

[a] Lancaster University; [b] Postharvest data missing

5.2.1 Soil moisture properties of experimental soils

The physiology studies of lettuce and onion growth were mainly undertaken in a polytunnel located next to the Crop and Environment Research Centre at HAU. The setup is described in detail in the Year 2 Annual Report. In brief, soil taken from the location of the polytunnel was amended with peat to give two defined uniform soils: 25% (high OM soil) or 5% (low OM soil) with which the bins were filled. Each bin had an access tube in the centre of the bin. The bins were filled from 16 to 23 March 2011 watered to saturation, allowed to settle and topped up on 14 April 2011. The soil was tilled to a depth of ~30cm after each crop and where needed bins were topped up with fresh substrate before the start of each experiment. The volume added was not recorded but was relatively small and not all bins needed topping up. The soil was not disturbed below 30 cm during the experiment. The soil properties of the unamended soil are shown in Table 3.

Table 3 *Unamended polytunnel soil properties.*

Soil property	Value
Organic matter OM (%)	2.26
Texture	Sandy loam
pH	6.4
P (mg/l)	68
K (mg/l)	142
Mg (mg/l)	71
Ammonium–N (mg/kgDM) 0-90 cm	7.22
Nitrate-N (mg/kgDM) 0-90 cm	10.00
Total N (g/100gDM) 0-90 cm	0.38
SMN (kg/ha) 0-90 cm	68.88

The soil moisture release curves of the new substrate mixes were established at the setup of the tubs (Figure 10) and showed a higher retention of water in the high OM substrate.

By the end of the experiment (Year 4) the soil moisture properties of the two soils, measured *in situ* in the top 20 cm were very similar to each other (Figure 11) and less than the initial values in Year 2. This can be explained by the fact that the soil in the bins had settled with frequent irrigation and that OM had degraded or been washed down the profile in the high OM soil over time.

Figure 10 *Soil moisture release curve for high OM and low OM substrates used in the soil bins (Year 2).*

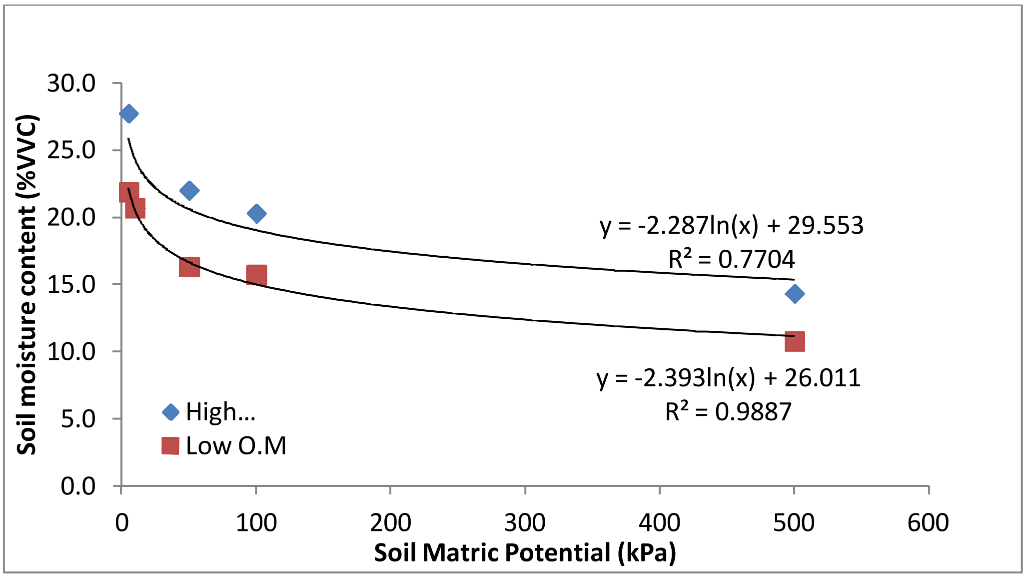
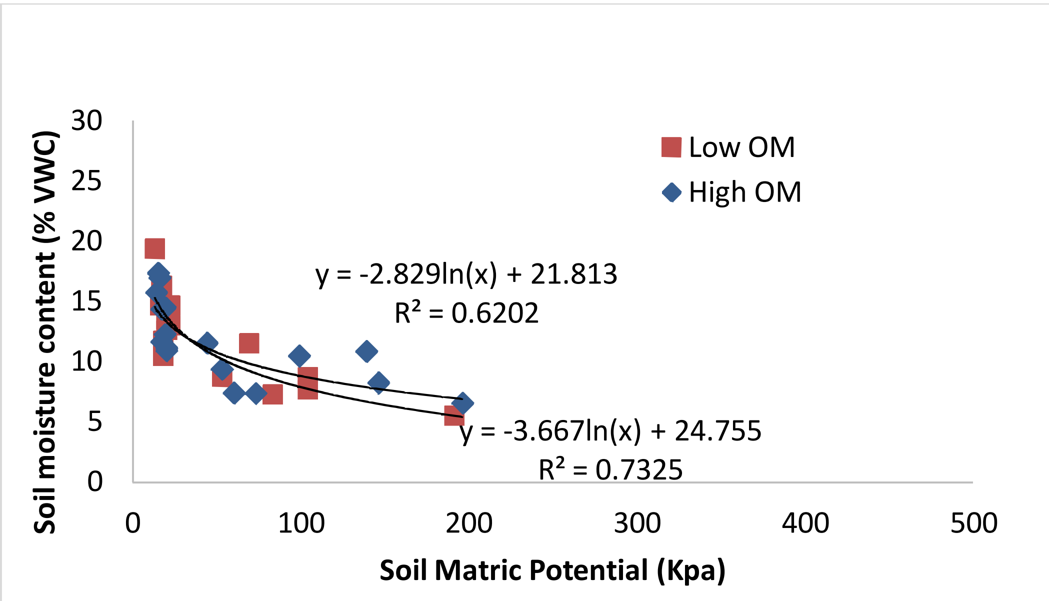


Figure 11 *Soil moisture release curve for high OM and low OM substrates used in the soil bins (Year 4).*



5.3 Understand how soil moisture variability relates to variability in crop water status (T2.1)

This work establishes the extent that, across a field crop in a variable climatic environment, soil water status would correlate with plant water status and hence how well an irrigation system linked to spatial and temporal variation in soil moisture status will be expected to mitigate drought effects on plant water status, growth and functioning.

Objective 2.1 was pursued with both lettuce and onion crops in Year 2 and was split into the following research questions, (i) what is the critical value of moisture content?, (ii) where in the profile should we measure soil moisture? And (iii) can we measure plant responses as a proxy for soil moisture need?

5.3.1 Establishing a critical value of moisture content (lettuce)

A glasshouse experiment at Lancaster University studied the response of lettuce to a drying environment. Lettuce (*cv* Chancellor) were transplanted into 4l pots with John Innes No. 2 compost and a range of irrigation treatments imposed from 60% to 110% evapotranspiration, ET. The experiment studied the relationship between stomatal conductance, canopy temperatures and soil moisture, as well as the yield response to deficit irrigation. The aim was to identify a threshold level for irrigation based on plant temperature, which is an indirect indicator of stomatal opening and water stress. Irrigation treatments of between 90% and 110% ET had similar levels of stomatal conductance (g_s) and values of Crop Water Stress Index ($CWSI = (T_{leaf} - T_{wet}) / (T_{dry} - T_{wet})$) in spite of large differences in soil moisture content (Figure 5), indicating a degree of plasticity in the plants adaptation to reduced water levels. Irrigation treatments in the range of 80% to 60% of ET had decreasing stomatal conductance (with decreasing soil moisture) and CWSI values over 0.5, indicating higher levels of stress. The threshold level where differences could be detected was below the 90% ET treatment. With the compost used in the experiment (John Innes No. 2), this corresponded to a volumetric water content of around 16% and an extrapolated soil matric potential of ~500 kPa.

Figure 12 *Stomatal conductance and crop water stress index of lettuce plants (HortGH01).*

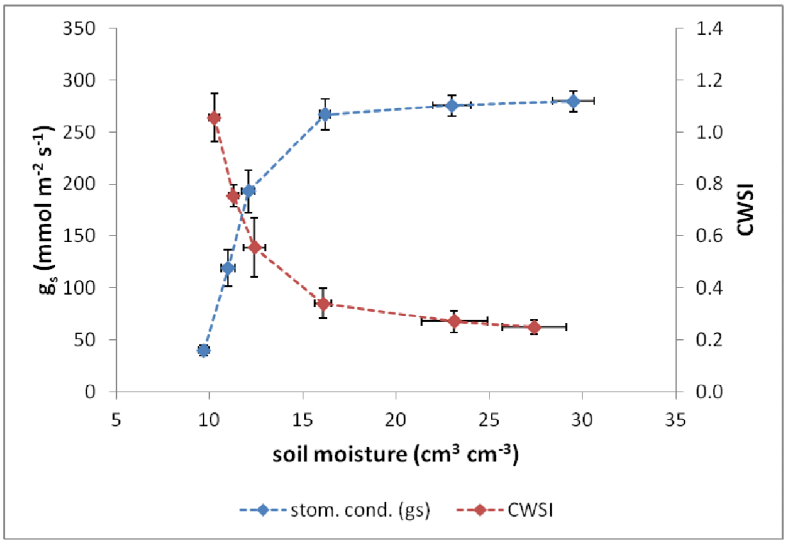
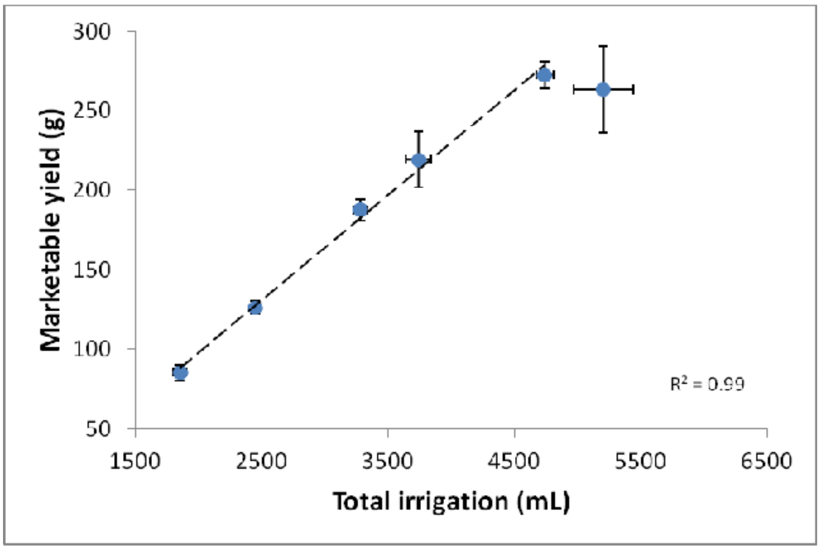


Figure 13 *Yield response of lettuce to increased irrigation. The treatments were based in replacing 60, 70, 80, 90, 100 and 110% of ET (HortGH01).*



The yield response to irrigation was highly linear between the 60% and 100% ET treatments, with even a small decrease in irrigation (to just 90% of ET) resulting in a significant decrease in yield (Figure 6). Therefore, if the aim is to obtain maximum yield, plant temperature does not seem to be a good indicator of water stress (and the need for irrigation) in lettuce: by the time the increase in temperature can be detected (threshold), yield will have already been affected. In summary:

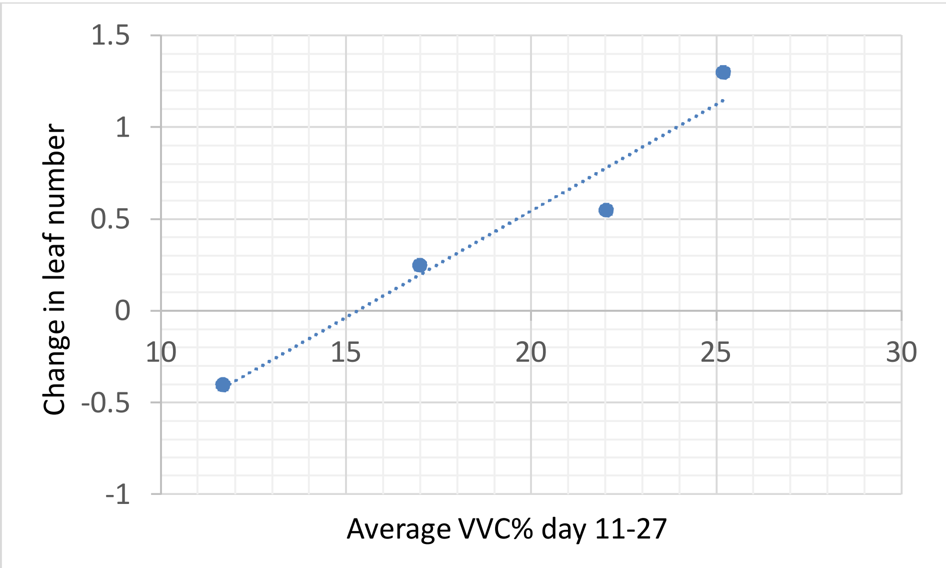
- Lettuce critical value ~16% VVC when stomata start to close;
- Equivalent to ~500 kPa;
- Yield reduction is observed before the critical soil moisture value is reached.

5.3.2 Establishing a critical value of moisture content (onion)

Work with established onion plants (HortOnion01) had not established plant responses that could be associated with a critical value of soil moisture content. This experiment looked at the number of green leaves in developing onion plants from the three leaf stage. Onion seedlings were grown in 1.75 L rectangular pots containing John Innes No. 2. Eighty pots were uniformly filled with sieved compost then placed on capillary matting and arranged in a random block design. The capillary irrigation was programmed to turn on for five minutes three times a day for the duration of the experiment. The pots were maintained at close to pot capacity until seeds had germinated and plants had 3 true leaves. The pots were weighed twice a week and VWC was measured using a theta probe. Treatments were imposed to generate a range of soil moistures; the well watered controls (Treatment 1) remained on the capillary matting but three treatments were placed on upturned saucers and either allowed to dry down (Treatment 2) or had 33% (Treatment 3) or 66% (Treatment 4) of weight lost replaced as water. The weight of biomass accumulation between readings was regarded as negligible for the calculation. Each pot contained 6 plants and each treatment had 20 pots. The experimental unit was one pot containing 6 onion plants. For the purposes of this experiment the onions were grown for 28 days. Green leaf number was counted day 0, 11 and 27.

The increase in green leaf number responded to soil moisture and suggested a critical value of 15% VWC below which the number of green leaves on the young onion plants declined (Figure 14).

Figure 14 *Relative changes in green leaf number on young onion plants correlated with average VWC over the same time period. Treatments started when all the plants had 3 leaves (HortGH02).*



- In summary, there is a critical value in young plants ~15% VVC (~560 kPa) when the number of green leaves declines.

5.3.3 Where in the profile should we measure soil moisture (onion)

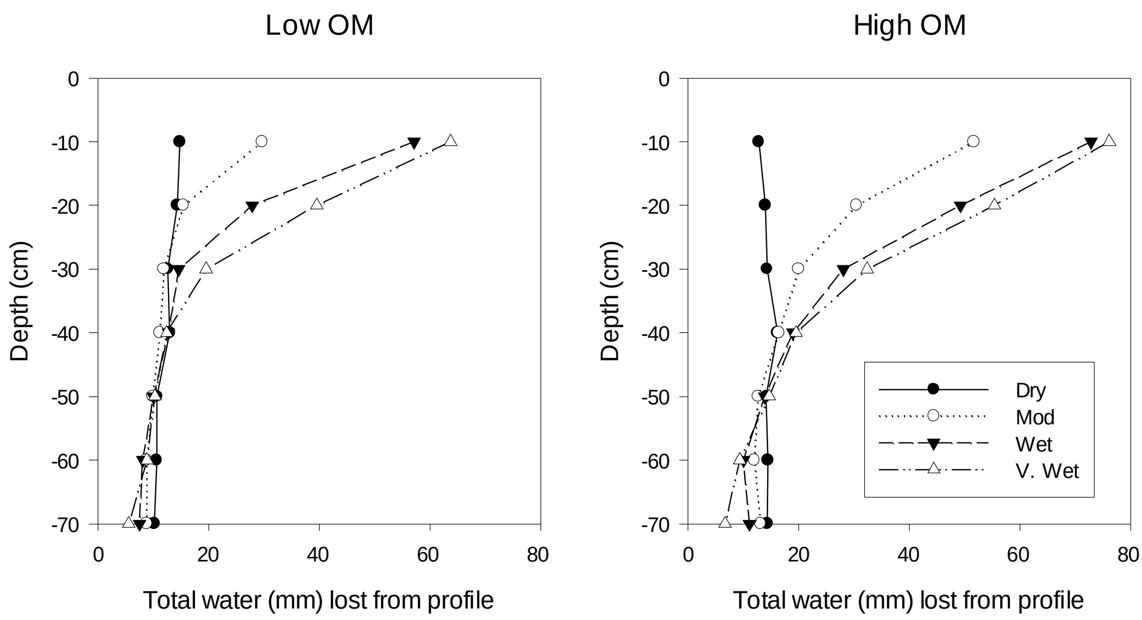
Detail provided in Year 2 Annual Report (HortOnion01). The use of a diviner probe in each bin allowed changes in soil moisture through the profile to be recorded over the development of the crop. The pattern of water use through the profile changed over the course of the experiment. In general, the irrigated treatments behaved similarly with the unirrigated, dry treatment responding differently. In the irrigated crops the majority of water lost between irrigation events was lost from the top 40 cm of the profile. Some of this will have been loss due to evaporation. The greatest water loss was observed in the treatments with the highest level of irrigation. In contrast the bins that were unirrigated showed that the plants were taking water from progressively deeper in the profile as the crops developed with water being lost from the bottom of the bins (70cm) in the last 4 weeks before harvest of the experiment. Both soils showed similar responses but, overall, the high OM soil showed a wider range of response.

Total water loss over the course of the experiment varied with treatment with the greatest loss from the irrigated treatments at 10 cm depth (Figure 15). Water loss in the unirrigated treatment was similar at all depths but the water lost in the irrigated treatments declined with depth and this effect was more marked in the high OM soil. At the bottom of the profile (50-70 cm) the dry treatment lost more water than the irrigated treatments in both soils.

In summary:

- The experiment generated a wide range of deficits. As these developed, the onion plants accessed water from deeper in the profile;
- This use of progressively deeper water was observed in all treatments but was proportionally greatest in the dry treatment and least with very wet treatment, and;
- The water use in the top 40 cm was most important for the irrigated treatments but includes an unquantified proportion of evaporative loss.

Figure 15 *Accumulated weekly water loss (mm) from the profile (HortOnion01.*



5.3.4 Where in the profile should we measure soil moisture (lettuce)

Detail provided in Year 2 Annual Report (HortLett02). The use of a diviner probe in each bin allowed changes in soil moisture through the profile to be recorded over the development of the crop.

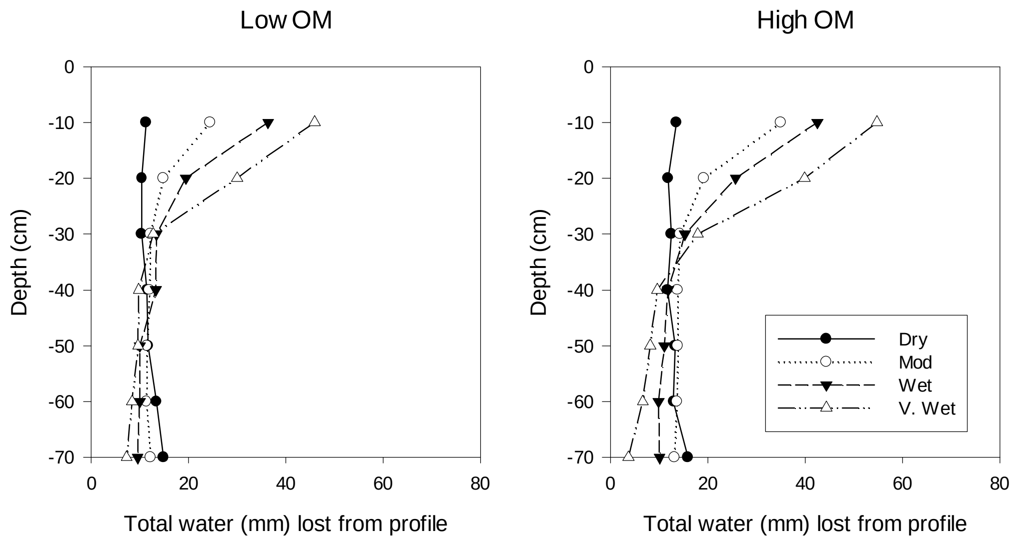
The pattern of water use through the profile changed over the course of the experiment. The pattern of response was similar for both soils. In the first two weeks the majority of water use was occurring in the top 20 cm of the bins. By the third week the dry treatments were using less water from the top 10 cm than the irrigated treatments. The depth of peak water use increased to 30-40 cm by the following week for all but the very wet treatment in week 4 and this pattern of peak water use moving down the profile continued for the next two weeks for all treatments except very wet. In week 6, the proportion of water use in the lower profiles started to decline relative to the top 20 cm and by the final week (week 7) very little water was being used from 30 – 70 cm in the irrigated treatments.

Water loss over the whole experiment varied with treatment with the greatest loss from the irrigated treatments at 10 cm depth (Figure 16). Water loss in the unirrigated treatment was similar at all depths but the water lost in the irrigated treatments declined with depth and this effect was more marked in the high OM soil. At the bottom of the profile (50-70 cm) the dry treatment lost more water than the wet and very wet treatments in both soils.

In summary:

- The experiment generated a wide range of SMD. As these developed, the lettuce plants accessed water from deeper in the profile;
- The use of progressively deeper water was observed in all treatments but was proportionally greatest in the dry treatment and least with very wet treatment, and;
- The water use in the top 30 cm was most important for the irrigated treatments but includes an unquantified proportion of evaporative loss.

Figure 16 *Total water loss calculated from weekly SMD (HortLett02).*

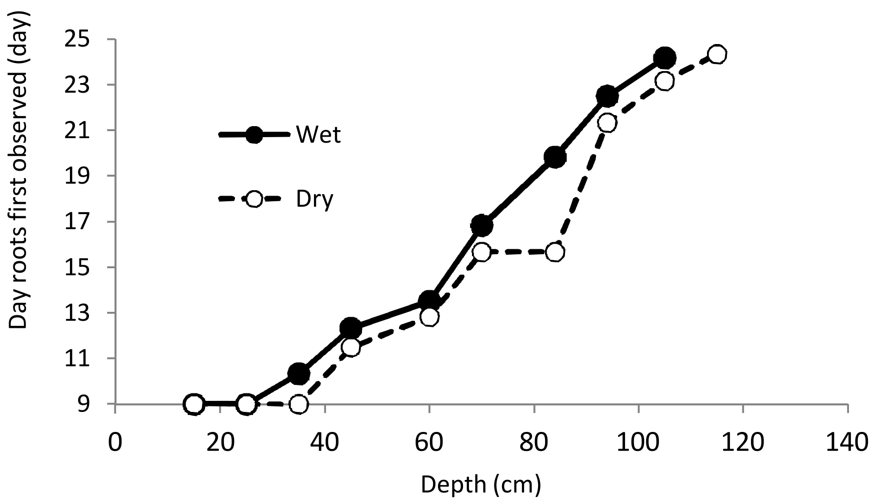


5.3.5 Distribution of lettuce roots in a drying soil

Detail provided in Year 2 Annual Report (HortRhizo01). Iceberg lettuce plants (cv Challenger) were grown from transplants in split rhizotrons (7 x 27 x 130 cm for each independent compartment).

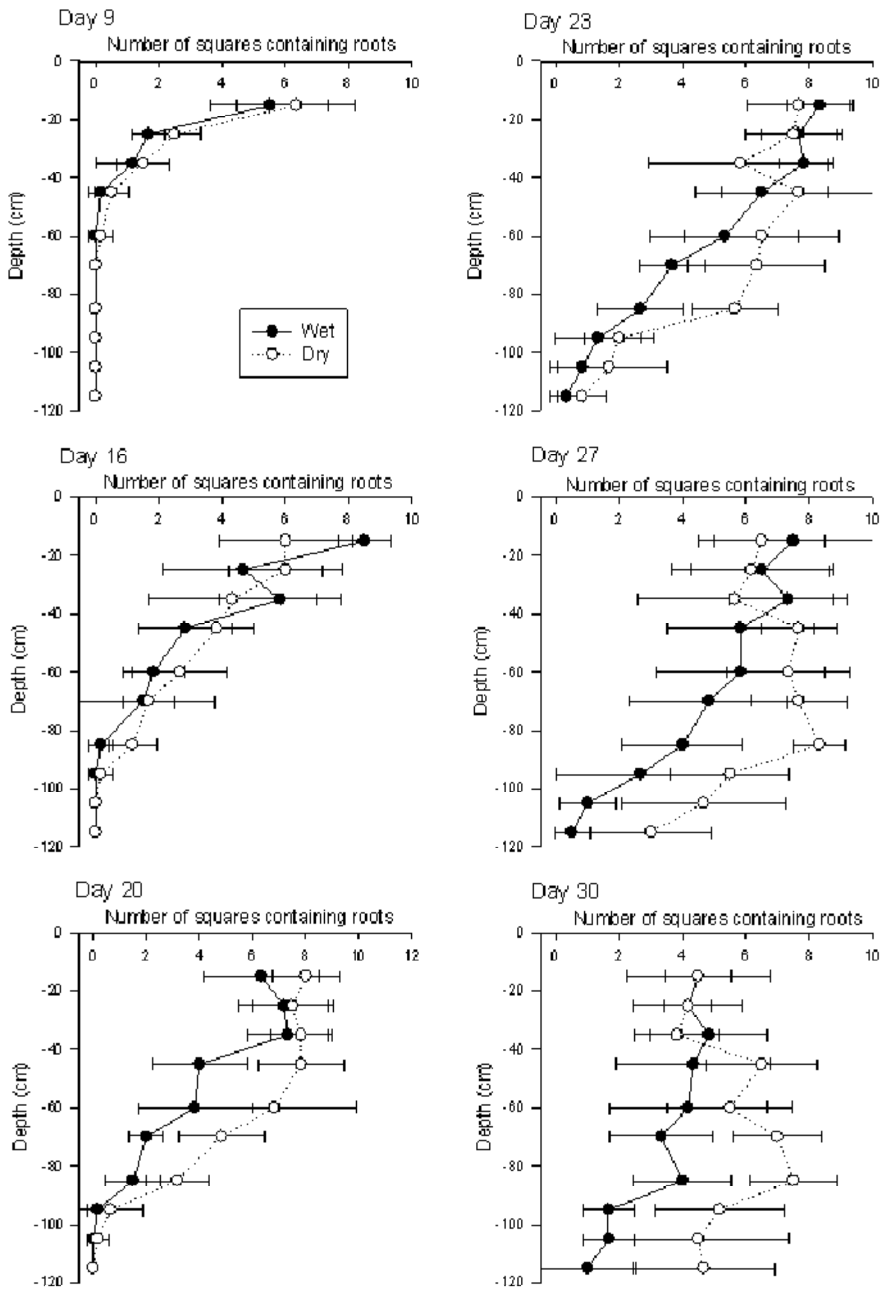
Rhizotrons were filled with soil taken from the location of the polytunnel and amended with 25% to give a similar soil to the high OM bins. The soil was passed through a screen to produce a defined uniform soil. Rhizotrons were watered to FC and one transplant placed in each independent compartment. During imposition of treatments total soil moisture at five depths (20, 40, 65, 90 and 110 cm) was measured in each bin 3 times a week on Monday, Wednesday and Friday morning using a theta probe inserted through capped access holes in the back of the rhizotron. The SMC was calculated for each zone and summed to give a total SMC for the rhizotron compartment. Calculated volumes of irrigation water were applied from the surface on Monday, Wednesday and Friday afternoons. Irrigation volumes were calculated from the summed deficits for each compartment as follows: Very wet – returned to 100% FC and Dry – no water added. Both wet and dry treatments rooted at similar rates. The dry treatment reached each level on average one day quicker than the wet treatment (Figure 10).

Figure 17 *Average days for first root to attain depth (HortRhizo01).*



The distribution of roots was similar between the treatments after 9 and 16 days (Figure 18).

Figure 18 *Number of roots observed down rooting profile in rhizotron grown lettuce (HortRhizo01).*



Roots were visible down to 45 cm after nine days and 95 cm after 16 days. After 20 days the dry treatment had more roots between the 35 and 85 cm. The difference between the two treatments reduced at day 23 although the number of roots at depth was still increasing in the dry treatment. In addition, the wet treatment had more roots from 15 to 35 cm relative to the dry treatment. This pattern remained the same after 27 days. By day 30, the number of roots in the top 35 cm of the rhizotron had declined in both treatments but relatively more so in the wet treatment. The distribution of roots had increased at depth in the dry treatment with a similar distribution of roots being observed from 15-35 cm as 95-115 cm in the dry treatment and, by the end of the experiment, the wet treatment had fewer roots than the dry treatment at all depths below 35 cm.

- Lettuce plants produced more, deeper roots in response to a developing soil moisture deficit down the profile;
- Lettuce roots grew to >1m in 23 days.

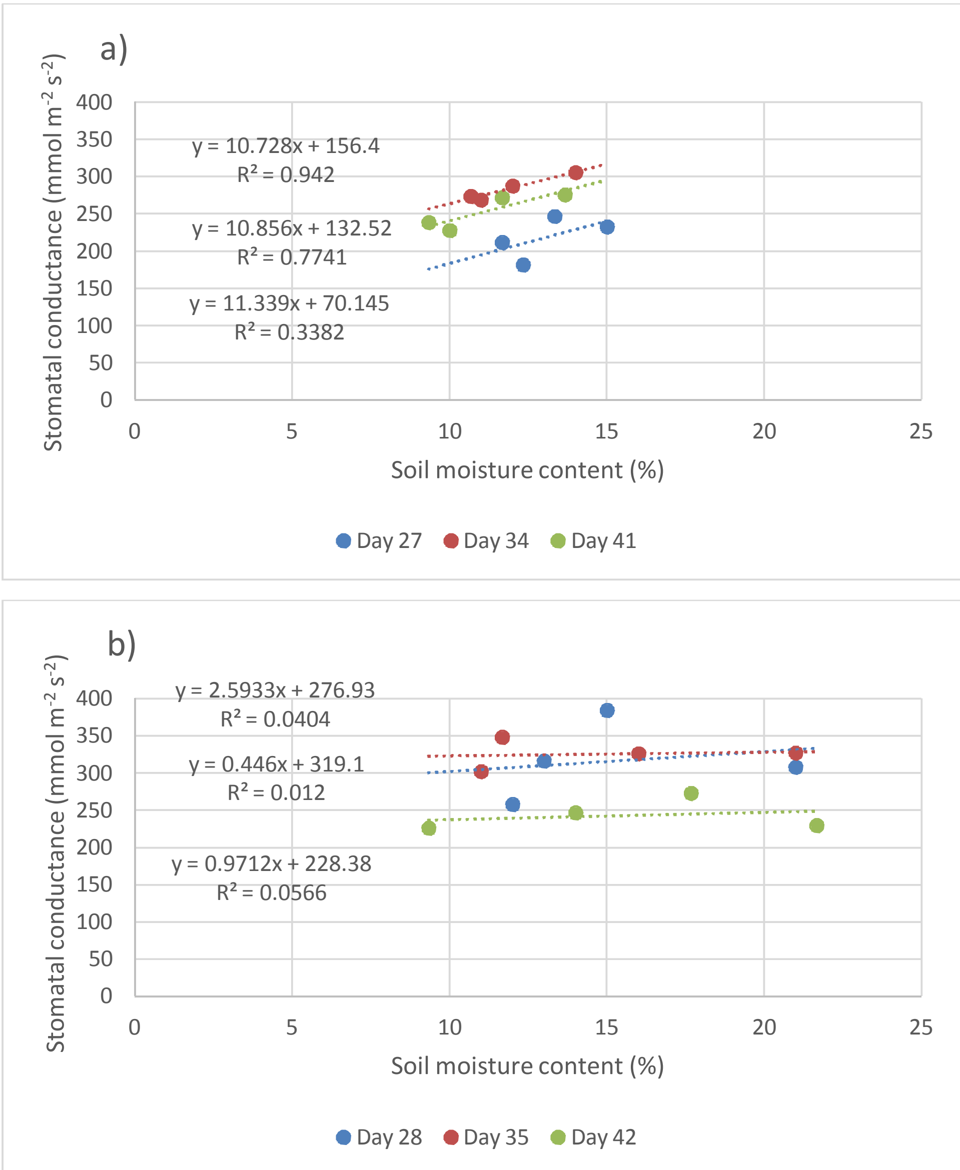
5.3.6 Can we measure plant responses as a proxy for soil moisture need (lettuce)

Detail provided in Year 2 Annual Report (HortLett01 & HortLett02). Two lettuce crops were grown in the soil bins with managed irrigation with 4 irrigation levels. HortLett01 was a preliminary trial and the data is not discussed here. The following plant responses were measured in the high OM soils and correlated with soil moisture content over 30 cm to establish whether plant responses to a drying soil could be used as an alternative to direct soil moisture readings. The responses measured were stomatal conductance, crop water stress index, relative water content, leaf number and leaf extension.

Stomatal conductance

In general, the stomatal conductance of the dry treatment was lower than the irrigated treatments. There was no overall correlation observed between stomatal conductance and soil moisture content. However, a consistent relationship between soil moisture and stomatal conductance was observed on the day before irrigation, when the differences in soil moisture content between treatments were relatively large. This relationship disappeared the day after irrigation (Figure 19).

Figure 19 *Stomatal conductance a) 3 hours before and b) 16 hours after irrigation with observed average soil moisture content 0-30cm for High OM soil treatments. (HortLett02).*



CWSI

The data from CWSI were very variable and the values for midday readings did not show significant differences or correlate with soil moisture.

RWC

*T*he relative water content of leaves generally increased from dry to v. wet treatment at day 29, but this was not significant.

Leaf growth

Neither the number of fully expanded lettuce leaves per plant nor the length of these leaves responded significantly to irrigation treatment in either soil.

- Crop water status measures based around stomatal function were variable. Stomatal conductance was correlated with soil moisture towards the end of the crop, when the differences in soil moisture were greatest between treatments;
- Neither CWSI nor RWC correlated with soil moisture;
- Leaf measurements did not respond to treatment and are not a good measure of soil moisture;
- Direct soil moisture measurement is the best way to schedule irrigation in lettuce.

5.3.7 Can we measure plant responses as a proxy for soil moisture need (onion)

Detailed provided in Year 2 Annual Report (HortOnion01). An onion crop was grown in the soil bins with managed irrigation with 4 irrigation levels. The following plant responses were measured in the high OM soils and correlated with soil moisture content to establish whether plant responses to a drying soil could be used as an alternative to direct soil moisture readings. The responses measured were stomatal conductance, Crop Water Stress Index, Relative Water Content, leaf number and leaf extension. Leaf measurements were limited by the fall over and senescence of leaves. This was particularly marked in the dry treatment where 25% of leaves had fallen over by 115 days after sowing (reported as day 41 in Annual Report) but irrigated treatments had less than 10% fall over.

Stomatal conductance

Stomatal conductance was measured on day 97, 102 and 111. When the data from the three dates was combined there was a linear response (R^2 = 0.68) showing a trend that stomatal conductance reduced with increased soil moisture. However, there was no correlation with soil moisture at days 97 or 102 or significant difference between treatments. By day 111 stomatal conductance reduced significantly with increased SMD (Fig 4).

CWSI

The data from CWSI was very variable even when the values for midday readings from only were compared. Overall the dry treatments exhibited greatest stress (i.e. were warmer) than the very wet treatments. The moderate and wet treatments did not differ significantly on any date.

RWC

The relative water content of leaves declined generally over time for all treatments.

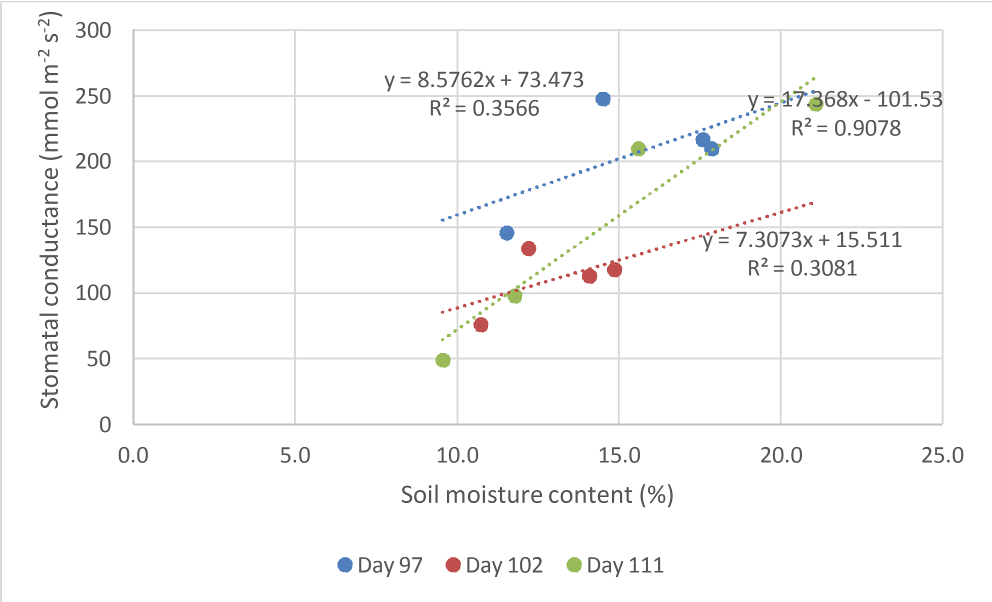
Leaf number

The production of leaves did not differ significantly with irrigation treatment. Overall the rate of production of leaves declined as the experiment progressed.

Leaf length

As plants grew bigger the fully expanded leaves were relatively longer. Leaf growth (i.e. extension) was relatively less in the dry treatment but the differences were not significant.

Figure 20 *Stomatal conductance correlated with average soil moisture (0-40cm) at day 97, 102 and 111 (HortOnion01).*



In summary:

- Crop water status measures based around stomatal function (i.e. stomatal conductance and CWSI) were variable and influenced by time of day and environmental conditions at the time of measurements;
- Relative water content and leaf growth measurements did not vary significantly with treatment, and;
- Direct soil moisture measurement is the best way to schedule irrigation in onions.

5.3.8 Conclusions

What is the critical value of moisture content?

Glasshouse experiments identified similar critical values for both crops with stomatal conductance responding at 16% VVC (500 kPa) in lettuce and green leaf number responding in young onion plants at 15% VVC (560kPa).

Where in the profile should we measure soil moisture?

Analysis of water loss/use through the profile of bin grown lettuce and onions showed that the top 30 cm (lettuce) and 40 cm (onion) are the zones of significant water use and are the zones that should be monitored for accurate assessment of soil moisture availability in a managed soil.

Plants of both crops exposed to extreme deficits accessed water progressively deeper in the profile. However, even low levels of irrigation led to water use in the top soil zone suggesting that this is the important area for functional water uptake.

Can we measure plant responses as a proxy for soil moisture need?

Not for commercial use. No plant measure was consistently associated with soil moisture status. Direct measurement of soil moisture is still required to manage precision irrigation of field vegetable crops.

5.4 How sensitive are crops to deficit irrigation stress during crop development (T2.2)

This objective is pursued using combined analysis of the experiments carried out in the polytunnels at HAU. The data and analyses were previously reported for the individual experiments in the Annual Reports and not referred to here. The aim of this objective was to study the response of the target crops to periods of irrigation stress at different stages of crop development. It was originally intended to impose controlled deficits at different times and define the relationships between stomatal conductance and leaf growth rate with plant and soil water status. Initial work (reported in T2.1) showed that in both lettuce and onion it was not possible to identify a relationship between plant growth measures and soil moisture deficit. Consequently this objective studies the effect of deficit stress applied at different times on final crop yield; T2.3 studies the effect of deficit stress and timing on crop quality.

5.4.1 Combined lettuce experiments

The timing of deficit and extent of stress differed between experiments. The deficit treatments are summarised in Table 4. Hortlet02 and Hortlet04 had early and late stress at different levels. Hortlet05-07 had repeats of early, mid and late deficits

Table 4 *Deficit timing and duration for lettuce experiments*.

Experiment	Week number						Duration of deficit (weeks)
	1	2	3	4	5	6	
Timing x extent of deficit							
Hortlett02	Low						6
	Med						6
	High						6
Hortlett04				Low			3
				Med			3
				High			3
Timing of deficit							
Hortlett02							6
Hortlett04							3
Hortlett05							3
							2
							1
Hortlett06							2
							2
							2
Hortlett07							2
							3
							1

5.4.2 Soil moisture deficit

The well watered (WW) control treatments were watered with a volume of watered calculated to return the bins to the target soil moisture content of 95% FC at each irrigation event during the experiments. Soil moisture contents of all bins were recorded approximately 2 hours before irrigation and 18 hours after irrigation. In some weeks, particularly when ET losses were high, the recorded soil moisture content of the WW treatments after irrigation did not reach the target level. In order to more accurately represent the relative water status of the deficit and WW treatments the weekly average maximum SMD (0-30 cm for Lettuce) for the deficit treatments was calculated from the respective WW SMD, and is termed the Relative Deficit (mm).

- Relative Deficit (SMD (mm) at 0-30 cm) = $SMD_{WW} - SMD_i$

The relative deficits were summed for the weeks that a deficit was imposed and termed Accumulated Relative Deficit (mm), allowing comparison between experiments of the extent of deficit imposed on the crops, relative to the WW control, which has an assumed value of 0 mm following each irrigation event. The experiments generated a range of accumulated relative deficits from 5 to 78 mm (Table 5).

Table 5 *Accumulated Relative Deficit (mm) imposed during deficit treatments for each experiment*.

Experiment	Duration of deficit	Week number	Accumulated relative deficit during treatment (mm)
	Extent of deficit		
Hortlett02	6	Wet 1-6	39
	6	Mod 1-6	70
	6	Dry 1-6	78
Hortlett04	3	Wet 4-6	5
	3	Mod 4-6	7
	3	Dry 4-6	12
	Timing of deficit		
Hortlett02	6	1-6	78
Hortlett04	3	4-6	12
Hortlett05	3	4-6	34
	2	5-6	18
	1	6	5
Hortlett06	2	1-2	8
	2	3-4	11
	2	5-6	25
Hortlett07	2	3-4	16
	3	4-6	54
	1	6	19

5.4.3 Growth measurements

In order to compare data from experiments relative measures of growth and marketable yield were derived:

- Relative marketable yield (% WW) = $(MY_i/MY_{ww})*100$
- *Relative circumference (% WW) =* $(Circ_i/Circ_{WW})*100$
- Relative yield response (relative marketable yield loss per mm relative deficit) = $((MY_i/MY_{ww})*100) / (SMD_{WW} - SMD_i)$

Soil OM had a significant effect in HortLett02 but there was no interaction between soil OM and irrigation treatment. There was no effect of soil OM in subsequent lettuce experiments hence, for comparison between experiments, the treatment responses for each experiment were averaged across soil OM (n=12).

5.4.4 Marketable yield

Actual marketable yield of the WW control plants varied between experiments ranging from an average 274 g head^{-1} in Hortlett02 to 576 g head^{-1} in Hortlett04 (Table 6). This can be explained to some extent by the different growing conditions for each transplanting.

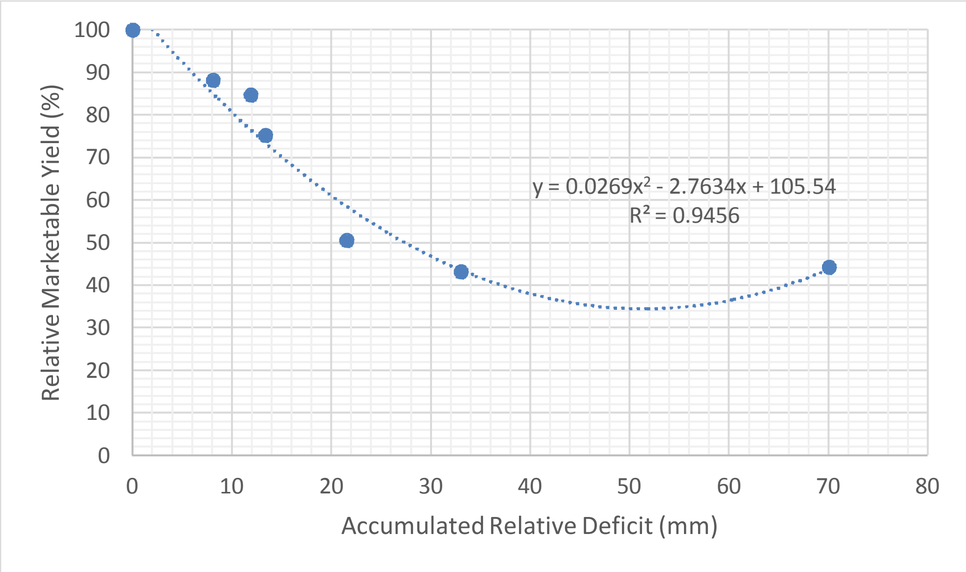
Table 6 *Marketable yield and relative marketable yield for experiments that addressed Objective 2.2.*

Experiment	**Duration of deficit**	**Week number**	**Marketable yield (g FW/head) average of 4 heads per bin**	**Relative marketable yield (% WW)**
	Extent of deficit			
Hortlett02	-	**WW**	**274**	100
	6	Wet 1-6	189	69
	6	Mod 1-6	122	44
	6	Dry 1-6	104	38
Hortlett04	-	**WW**	**576**	100
	3	Wet 4-6	325	57
	3	Mod 4-6	325	44
	3	Dry 4-6	252	44
	Timing of deficit			
Hortlett02	-	**WW**	**274**	100
	6	Dry 1-6	104	38
Hortlett04	-	**WW**	**576**	100
	3	Dry 4-6	252	44
Hortlett05	-	**WW**	**427**	100
	3	4-6	179	42
	2	5-6	228	53
	1	6	366	86
Hortlett06	-	**WW**	**483**	100
	2	1-2	426	88
	2	3-4	416	86
	2	5-6	231	48
Hortlett07	-	**WW**	**352**	100
	2	3-4	227	64
	3	4-6	155	44
	1	6	295	84

5.4.5 Effect of deficit on marketable yield

Withholding irrigation reduced final marketable yield in all treatments with the lowest yield, 38% of WW, observed with the 6 week deficit in Hortlett02 (Table 6). The smallest yield response was 88% of WW following a deficit in week 1-2 in Hortlett06 (Table 6). This response can be explained to some extent by the accumulated deficit of each treatment rather than timing (Figure 21) where larger deficits were associated with a greater relative reduction in yield to a limit of approximately 40%.

Figure 21 *Relationship between accumulated relative deficit and relative marketable yield. Each data point represents an average value for identical deficit treatments. Only treatments where water was withheld were included along with WW control.*

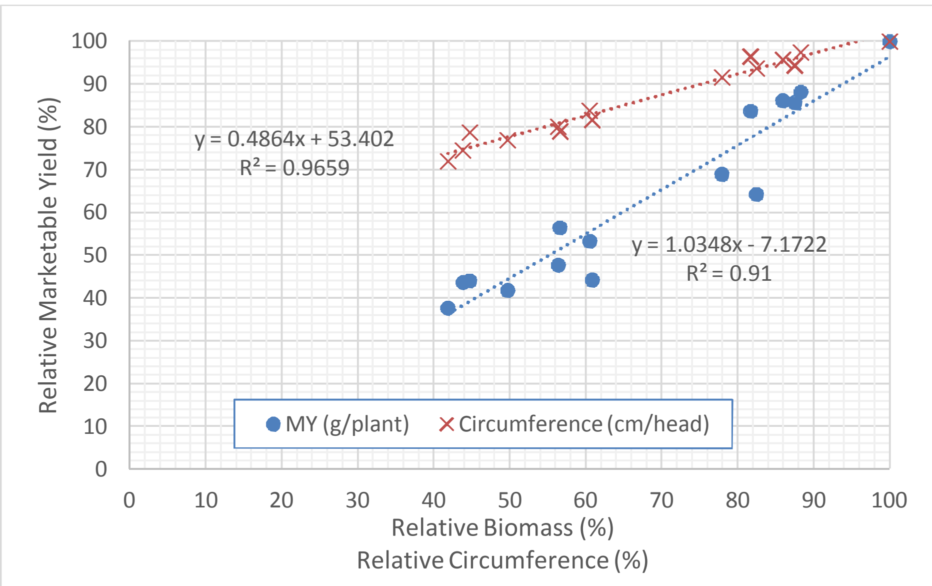


- Total biomass and trimmed head circumference reduced as deficits increased.
- Deficits did not lead to a disproportionate increase in the weight of waste leaves.

5.4.6 Effect of deficit on total plant biomass and trimmed head size

The total plant growth (untrimmed biomass) responded in a similar manner to marketable yield and there was a consistent linear relationship close to y=1 between relative marketable yield and relative biomass for all treatments (Figure 22). This shows that the proportion of waste i.e. trimmed material did not increase. There was also a consistent linear relationship between relative marketable yield and relative circumference but the reduction in circumference was smaller than the reduction in yield as deficits increased. This suggests the heads were becoming less dense as deficits increased.

Figure 22 *Relationship between accumulated relative deficit and relative marketable yield and relative circumference. Each data point represents average value for individual treatments.*

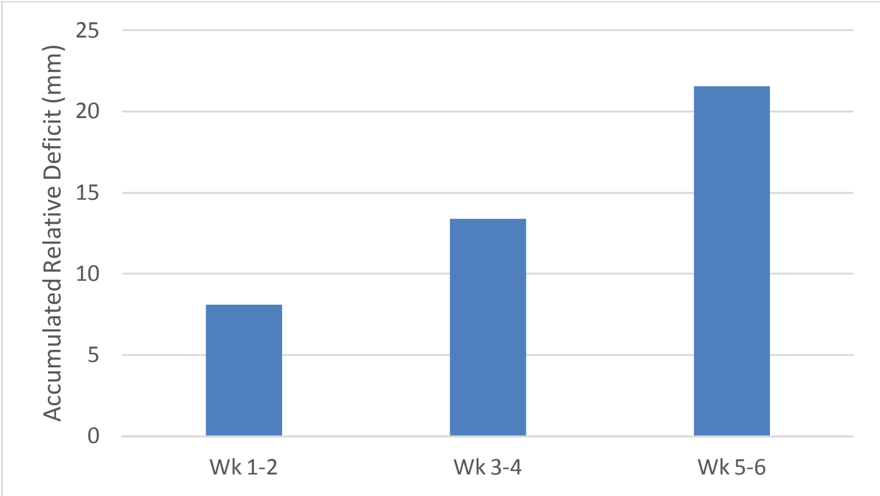


- The reduction in head circumference was slower than marketable yield showing that heads became less dense with increasing deficit.

5.4.7 Effect of timing of deficit on marketable yield

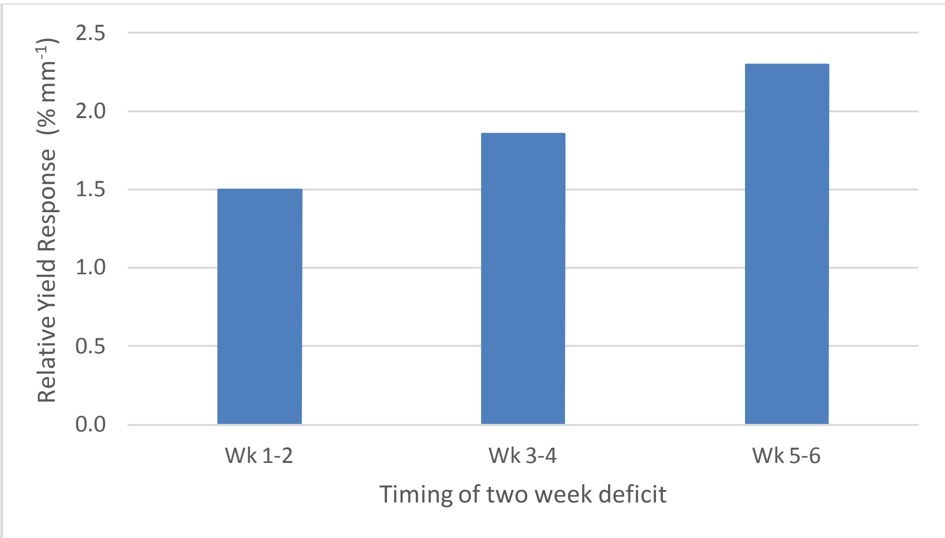
The experimental deficit treatments differed in extent (Hortlett02 and 04), timing (all) and duration (all) of deficits. Deficits were imposed by withholding irrigation from the bins. However, the extent of deficit depended on the amount of water lost from the bin through evapotranspiration (ET) and ET was greater as the plants increased in size and leaf area. As a consequence the extent of deficit imposed for the same duration increased during the experiment (Figure 23) with a deficit of 8.1, 13.4 and 21.5 mm where irrigation was withheld for two weeks from Week 1, 3 and 5, respectively.

Figure 23 *Accumulated relative deficits (0-30cm) for treatments where irrigation was withheld for two weeks starting at week 1, 3 and 5.*



However, the percentage yield loss was more sensitive to deficit the later the deficit was imposed. Each mm of relative SMD imposed during weeks 1 and 2 reduced marketable yield by 1.5% compared to the WW treatment. Imposing a deficit in weeks 5 and 6 reduced marketable yield by 2.3% compared to the WW treatment (Figure 32).

Figure 24 *Relative yield responses for treatments where irrigation was withheld for two weeks starting at week 1, 3 and 5.*



- It is harder to impose deficits on lettuce at the start of the crop cycle due to low ET;
- The size of the deficit correlates with final yield;
- The yield loss per mm of deficit increases as the crop develops, and;
- Imposing a deficit irrigation regime on lettuce will lead to a yield reduction regardless of timing.

5.4.8 Combined onion experiments

The timing of deficit and extent of stress differed between experiments. The deficit treatments are summarised in Table 7. Hortonion01 imposed deficits at different levels from leaf 7 and Hortonion01-03 imposed deficits from leaf 7 (01 - Dry), leaf 6 for 8 weeks (02), leaf 7, 9 and 10 (03).

Table 7 *Deficit timing and duration for the onion experiments (Objective 2.2).*

Experiment	Week number													Duration of deficit
	8	9	10	11	12	13	14	15	16	17	18	19	20	
Extent of deficit														
HortOnion01				W										9
				M										9
				D										9
Timing of deficit														
HortOnion01														
HortOnion02														9
														9
HortOnion03														9
														8
														7

5.4.9 Soil moisture deficit

The same approach to SMD was taken in the onion experiments as described for the lettuce experiments. The weekly average maximum SMD (0-40 cm for onions) for the deficit treatments was calculated from the respective WW SMD, and termed relative deficit (mm).

- Relative Deficit (SMD (mm) at 0-40 cm) = $SMD_{WW} - SMD_i$

Accumulated relative deficit (mm) allows comparison between experiments for the extent of deficit imposed on the crops, relative to the WW control, which has an assumed value (0 mm) following each irrigation event. The experiments generated a range of accumulated relative deficits from 62 – 225 mm (Table 8).

Table 8 *Accumulated relative deficit (mm) imposed during deficit treatments for each experiment.*

Experiment	Duration of deficit	Week number	Leaf number at start of treatment	Accumulated relative deficit during treatment (mm)
	Extent of deficit			
HortOnion01	9	Wet: 11-19	7	102
	9	Mod: 11-19	7	160
	9	Dry: 11-19	7	225
	Timing of deficit			
HortOnion01	9	11-19	7	225
HortOnion02	9	8-16	6	69
	9	8-13 &17-19	6 & 9	62
HortOnion03	9	12-20	7	224
	8	13-20	9	205
	7	14-20	10	165

5.4.10 Growth measurements

In order to compare data from experiments relative measures of growth and marketable yield were derived similarly to the lettuce experiments:

- Relative Bulb Weight (% WW) = $(BulbFW_i/BulbFW_{ww})*100$
- Relative Bulb Circumference $(\% WW) = (Circ_i/Circ_{WW})*100$
- Relative Yield Response (Relative Marketable Yield Loss per mm Relative Deficit) = $((BulbFW_i/BulbFW_{ww})*100) / (SMD_{WW} – SMD_i)$

Soil OM had a significant effect in HortOnion01 but there was no interaction between soil OM and irrigation treatment. There was no effect of soil OM in subsequent onion experiments hence, for comparison between experiments, the treatment responses for each experiment were averaged across soil OM (n=12).

5.4.11 Bulb fresh weight

Actual Bulb Fresh Weight for the WW control plants varied between the three experiments ranging from an average of 111 g bulb^{-1} in HortOnion01 to 135 g bulb^{-1} HortOnion03 (Table 9). The lower bulb weight in HortOnion01 may be due to 15 bulbs being grown per bin compared to 10 plants per bin in the subsequent experiments (equivalent to the industry standard rate of 50 m^{-2}).

Table 9 *Marketable yield and relative marketable yield for onion experiments (Objective T2.2).*

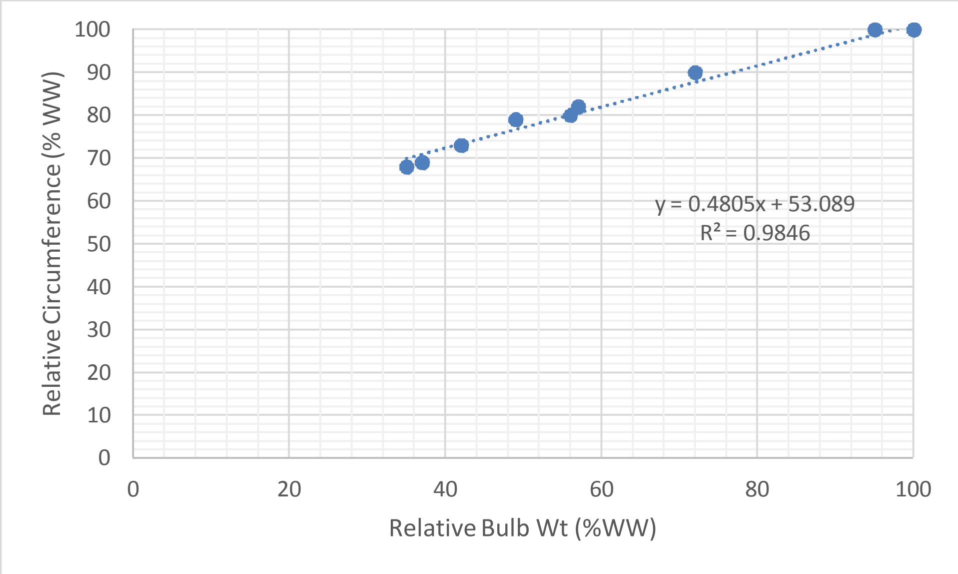
Experiment			Average bulb FW (g FW/bulb)	Relative bulb Wt (% WW)	Relative circumference (%WW)
	Extent of deficit				
HortOnion01	-	**WW**	**111**	100	100
	9	Wet: 11-19	105	95	100
	9	Mod: 11-19	80	72	90
	9	Dry: 11-19	55	49	79
	Timing of deficit				
HortOnion02	-	**WW**	**127**	100	100
	9	8-16	47	37	69
	9	8-13 & 17-19	71	56	80
HortOnion03	-	**WW**	**135**	100	100
	9	12-20	47	35	68
	8	13-20	56	42	73
	7	14-20	78	57	82

5.4.12 Effect of deficit on bulb fresh weight and size

Relative bulb weight decreased when irrigation was withheld (Table 9). The largest relative yield reduction was recorded for HortOnion03 where a deficit imposed from week 12 to 20 produced an average bulb fresh weight of 47g; 35% of the average bulb FW of the WW treatment. The smallest yield response was 95% of WW following a managed deficit from week 11-19 in HortOnion01 (Table 9). There was no overall relationship between accumulated deficit and relative bulb weight.

There was a linear relationship between relative bulb weight and relative circumference (Figure 25). The relationship showed that a 50% reduction in relative yield would be associated with a 25% reduction in relative bulb circumference i.e. deficits reduced yield more than circumference and that this relationship was consistent regardless of timing of deficit.

Figure 25 *Relationship between accumulated relative deficit and relative bulb weight and relative circumference. Each data point represents average value for an individual experimental treatment.*

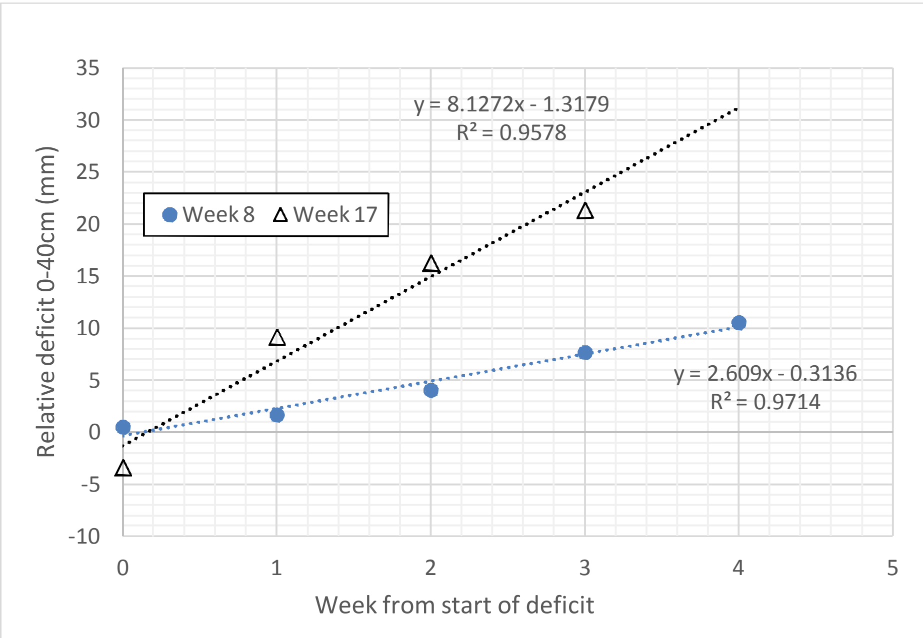


- Accumulated deficit is associated with reduced total biomass, bulb weight and circumference.

5.4.13 Effect of timing of deficit on bulb fresh weight

As with lettuce, the later in the growing season that irrigation is withdrawn the more rapidly a deficit develops as a consequence of increased water use (ET) by the larger crop. This was seen in HortOnion02 where the deficit imposed from week 17 developed approximately three times faster than one imposed from week 8 (Figure 26). This can explain the smaller accumulated deficits observed for HortOnion02. Nevertheless, the much larger yield reductions associated observed in HortOnion02 indicates that the early growth stages in onion are more sensitive to deficit.

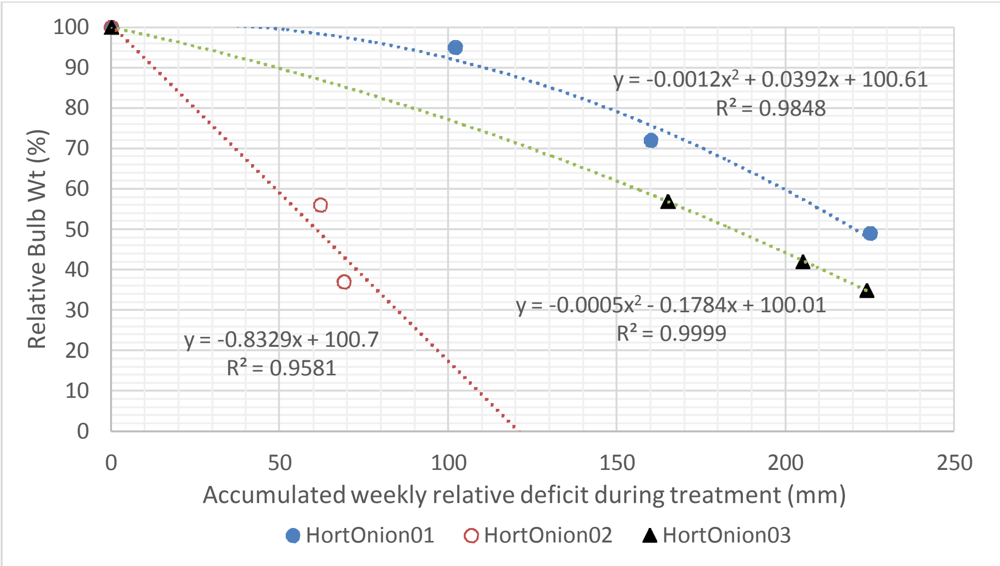
Figure 26 *Accumulated Relative Deficit (0-40cm) for treatments where irrigation was withheld starting at Week 8 and Week 17 (HortOnion02).*



- Early deficits are difficult to impose in onions due to low crop ET

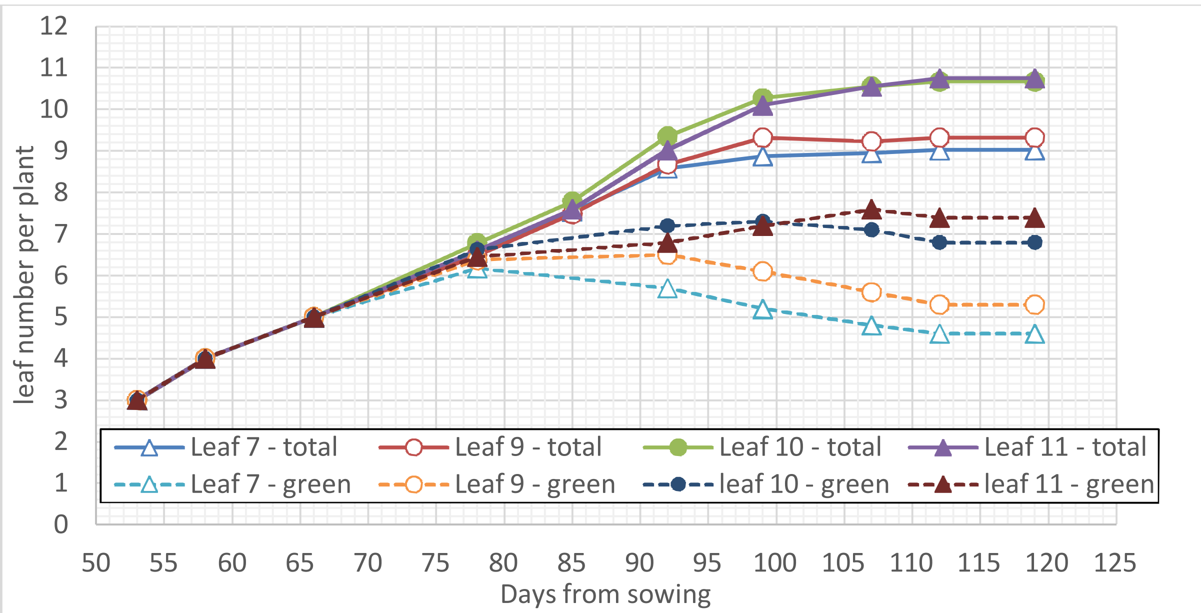
In contrast to lettuce, the response of relative yield to accumulated relative deficit during treatments did not fit a simple model suggesting that timing of deficit has a significant effect on onion growth. Whilst yield reduction was correlated with accumulated relative deficit in a similar pattern for HortOnion01 and HortOnion03, the reduction in relative bulb weight in response to accumulated deficit was more marked in HortOnion02 (Figure 27). The key difference between HortOnion02 and the other experiments is that deficits were imposed earlier, from leaf 6 (week 8) as compared to leaf 7 (week 11 and 12 in HortOnion01 and HortOnion03, respectively).

Figure 27 *Relationship between accumulated relative deficit and relative bulb weight for all three experiments along with WW control.*



HortOnion03 identified that deficits imposed before leaf 9 led to decline in green leaf number and limited development of further leaves (Figure 31) which influence both scale number and crop photosynthetic potential, reducing yield. The relative yield response showed a similar pattern with an average of 0.29% yield loss per mm accumulated deficit associated with deficits imposed from either leaf 7 or leaf 9 compared to a relative yield response of 0.26 with a deficit imposed from leaf 10.

Figure 28 *Total leaf number and green leaf number over time in response to deficit imposed from leaf 7 (fall of first leaf), 9 (bulb forming), 10 (bulb thickening) and 11 (fallover) - HortOnion03*



- Yield reduction is correlated similarly with accumulated deficit from week 11 (Hortonion01) and week 12 (Hortonion03)
- Leaf loss was more sensitive to drought stress than leaf number.
- Deficits imposed from Leaf 7 and leaf 9 reduced green leaf and total leaf no.
- Reduced green leaf number is associated with a reduced number of bulb scales

HortOnion02 enabled a comparison of late deficits imposed week 14-16 during bulb thickening to week 17-19 during leaf fallover. The relative bulb weight in HortOnion02 was small due to the early deficit imposed from week 8. Both late deficit treatments had a similar Accumulated Relative Deficit during treatment with 69 and 62 mm respectively (Table 10) but the week 14-16 deficit had a reduced yield leading to a relative yield response of 0.92 percentage points per mm deficit from the WW treatment compared to a value of 0.71 for the deficit imposed during week 17-19 i.e. yield was more sensitive to deficit during the early rather than later stages of bulb filling.

Table 10 *Relative bulb weight, accumulated relative deficit during treatment and relative yield response for the late deficit study. Both treatments had a background deficit imposed from week 8 to 13 (HortOnion02.*

Late deficit (after week 13)	Relative bulb weight (% WW)	Accumulated relative deficit during treatment (mm)	Relative yield response (% mm^{-1})
14-16	37	69	0.92
17-19	56	62	0.71

- Yield was more sensitive to deficit during the early rather than later stages of bulb filling

5.5 Impact of varying irrigation regime on crop yield and quality (T2.3)

HL0165LFV demonstrated that irrigation has a marked impact on yield and post-harvest quality of Batavia lettuce. Improved shelf life has been demonstrated in broccoli where water stress was imposed during head growth (Wurr *et al,* 2002). Using treatments informed by T2.1 and T2.2 a range of irrigation treatments were imposed on lettuce and onions under controlled experimental conditions. The development of the crops was monitored as in T2.1 and T2.2. In addition, post-harvest shelf life trials were undertaken in refrigerated environments. Visual appearance was scored following standard commercial protocols.

The effect of varying irrigation on yield was covered in Objective 2.2 where yield was used as a measure of sensitivity to irrigation timing. In this work, the same experiments were used and thus the table of treatments are not represented (see Objective 2.2). This objective focussed on quality responses in both lettuce and onions to answer the question: can postharvest quality be manipulated through irrigation regime? The objective thus informs the trigger points for irrigation scheduling and how they change at different stages of crop development. The key findings are summarized below.

5.5.1 Lettuce

In all experiments, four lettuces were harvested from each bin on Day 0, trimmed to a marketable head following commercial practice wrapped in perforated plastic bags and stored in a cold store at 3°C. Initial assessments were made on the day of harvest and post-harvest assessments were made 10, 20 and 30 days after harvest on one head per bin. An outer leaf was removed from each head and solute leakage was determined (see Annual Reports for methodology). Visual scoring of quality followed the visual assessment criteria supplied by Gs Marketing for appearance, external breakdown, chill damage, tipburn, pest presence, pest damage, disease, dehydration, delamination, soiling, rib cracking, rib bruising, pinking, ribbyness, butt discoloration, breakdown, bolting and misshapen head. The heads were then weighed fresh and dried in an oven at 80°C for 5 days before the dry weight was recorded and the moisture content calculated.

Following discussion with commercial partners involved in the project, pinking was identified as the key post-harvest quality parameter for study. Pinking develops during storage and the expression of pinking in the ribs at day 20 was chosen as it showed significant difference between treatments. It should be noted that most lettuce will be a maximum of 10 days old in the retail supply chain and day 20 was chosen as a typical storage duration. In order to compare data from experiments a relative measure of pinking was derived:

Relative pinking (% WW) = *(Pinking score$_i$/Pinking score$_{ww}$)*100*

The average pinking score and relative pinking are shown for each experiment in Table 11 along with a summary of conditions for each experiment.

Table 11 *Deficit extent and timing, accumulated relative deficit during treatment, pinking score (day 20) and relative pinking imposed during deficit treatments (experiments for Objective 2.3).*

Experiment	Duration of deficit	Week number	Accumulated relative deficit during treatment (mm)	Pinking d20 (0 = no pinking, 3 = severe pinking)	Relative pinking (%WW)
	Extent of deficit				
Hortlett02	-	**WW**	0	**1.4**	100
	6	Wet 1-6	39	0.6	45
	6	Mod 1-6	70	0.1	4
	6	Dry 1-6	78	0	0
Hortlett04	-	**WW**	0	**1.8**	100
	3	Wet 4-6	5	1.8	100
	3	Mod 4-6	7	-	-
	3	Dry 4-6	12	1.2	67
	Timing of deficit				
Hortlett02	-	**WW**	0	**1.4**	100
	6	Dry 1-6	78	0	0
Hortlett04	-	**WW**	0	**1.8**	100
	3	Dry 4-6	12	1.2	67
Hortlett05	-	**WW**	0	**2.7**	100
	3	4-6	34	1.1	41
	2	5-6	18	1.3	50
	1	6	5	2.5	94
Hortlett06	-	**WW**	0	**1.4**	100
	2	1-2	8	1.3	94
	2	3-4	11	1.2	82
	2	5-6	25	0.3	18
Hortlett07	-	**WW**	0	**2.8**	100
	2	3-4	16	0.8	30
	3	4-6	54	1.1	41
	1	6	19	2.0	72

5.5.1.1 Effect of deficit on lettuce pinking

Pinking was observed after 20 days in lettuces from the WW control for all experiments. The amount of pinking in the WW plants varied between experiments from a score of 1.4 in Hortlett02 and Hortlett06 to 2.8 in Hortlett07. Interestingly, the higher values were observed in the crops transplanted later in the year with HortLett05 and Hortlett07 being transplanted in July in 2012 and 2013, respectively. Initial data suggested that here was a link between moisture content (MC %) in the trimmed head at harvest and subsequent pinking. This association was present for each experiment with higher moisture contents at harvest being associated with greater pinking but the level of pinking at an absolute value of moisture content was not consistent (Figure 29).

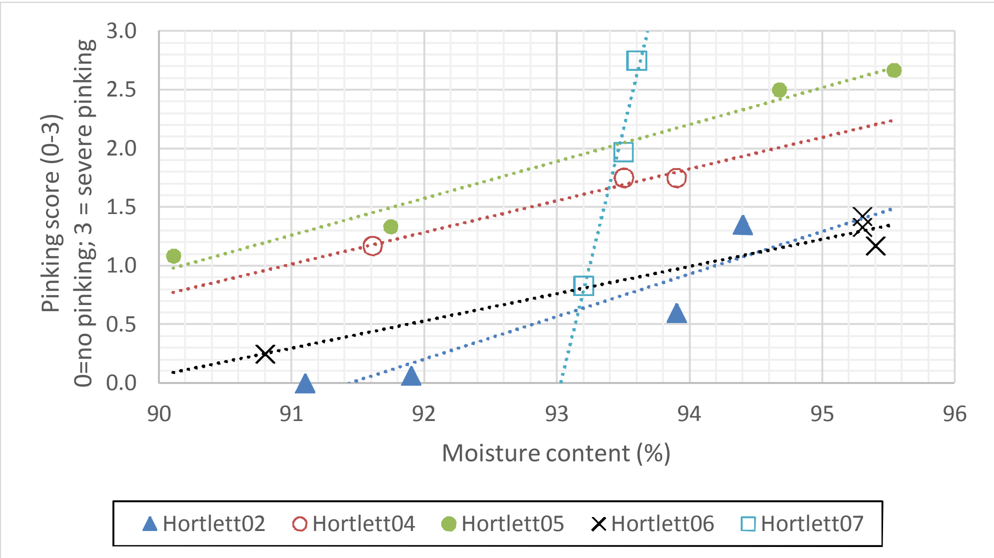
- The level of pinking after 20 days in well watered control plants differed between experiments;
- Within each experiment pinking was lower in heads with lower MC% at harvest.

In order to compare the relationship between pinking and a range of factors, relative pinking was derived and correlated with relative marketable yield, relative biomass, moisture content at harvest and accumulated relative deficit during treatment (Table 12).

Table 12 *Correlation of relative pinking, accumulated relative deficit during treatment, relative marketable Yield, relative biomass and moisture content at harvest. Treatment means were included from all experiments. (*=p<0.05; **=p<0.001).*

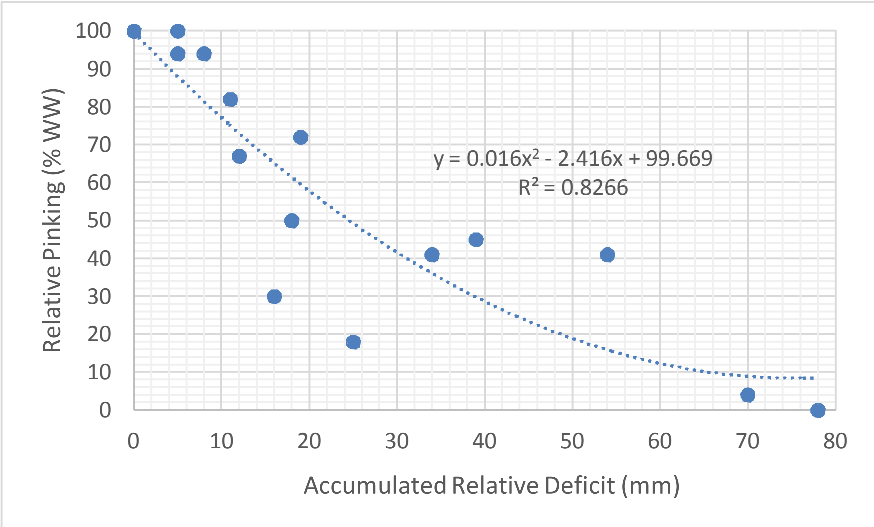
	Relative pinking
Accumulated relative deficit during treatment	-0.83**
Relative biomass	0.47*
Relative marketable yield	0.65**
Moisture content	0.58*

Figure 29 *Relationship between moisture content (%) of the head at harvest and expression of pinking score after 20 days cold storage.*



Relative pinking was significantly (p<0.001) negatively correlated with accumulated relative deficit during treatment i.e. the greater the extent of deficit the less pinking developed. In contrast, relative pinking was significantly positively correlated with moisture content in the head at harvest and relative measures of biomass and marketable yield. The relationship between accumulated relative deficit during treatment and relative pinking is described by the equation $y = 0.016x^2 - 2.416x + 99.669$ (Figure 30). This relationship suggests that the extent of pinking in lettuce 20 days after harvesting could be reduced by 50% through imposing of a deficit of 25mm.

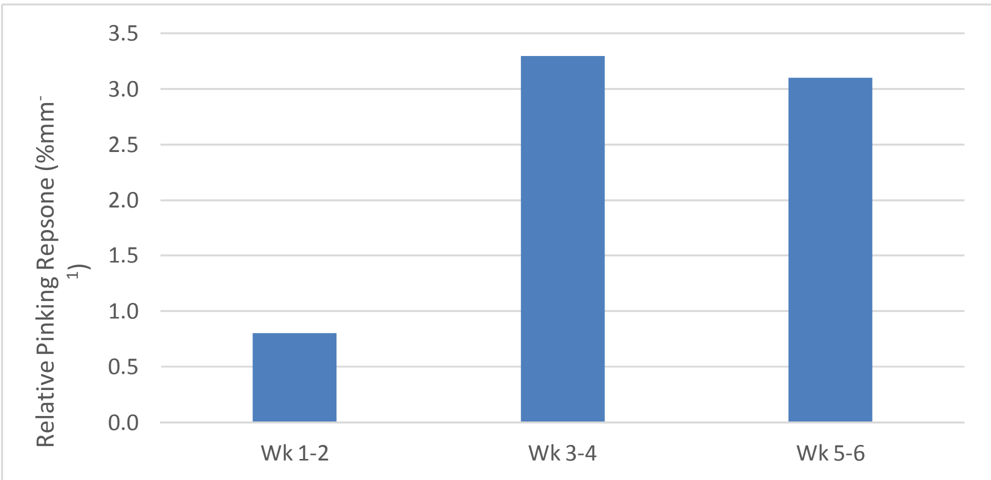
Figure 30 *The relationship between Accumulated Relative Deficit and Relative Pinking after 20 days.*



5.5.1.2 *Effect of timing of deficit on lettuce pinking*

Objective 2.2 demonstrated that the deficits imposed early in the crop cycle were limited by low crop water use (ET). Nevertheless, the relationship in Figure 30 is derived from a range of timings of deficits. When the reduction in pinking relative to WW accounted for by the deficit imposed was calculated for three different timings it was clear that an early deficit has little effect on post-harvest quality (Figure 31). However, deficits from week 3-4 had a similar effect as those from week 5-6 suggesting that mid and late deficits have similar potential to reduce pinking in a crop.

Figure 31 *Relative pinking responses for treatments where irrigation was withheld for two weeks starting at week 1, 3 and 5.*



5.5.2 Onion

In all three experiments two bulbs from each plot were dried in an oven at 80°C for 5 days and the dry weight recorded allowing calculation of bulb dry matter proportions. The remaining onions were cured by lifting from the soil on and left to 'field cure' on top of the bins for ~3 days before being placed in a drying oven for 9 days at 30°C, followed by bin drying with ambient air for 24 days. Six bulbs per bin were stored in an unlit cold store at 1-3°C for storability assessment at 3 and 6 months.

Unfortunately, the onions from HortOnion03 were placed in error in a drying oven at 80°C rather than 30°C preventing any post-harvest assessment.

5.5.2.1 Post-harvest assessment

Onions were removed from storage and chopped in half. Internal sprout length was measured using a ruler. Internal sprout length was measured using a ruler as the distance from the basal plate to the tip of the shoot. Internal sprouts were defined as the first appearing green leaves inside the bulb. Onion bulbs were also scored as multi centred or single centred and general quality was observed and any moulds or rots recorded. An additional treatment was included in HortOnion02 where a deficit was imposed in week 17 and 18 but the bins were then flushed in week 19, prior to lifting the bulbs. This treatment was included to test the hypothesis that flushing a crop prior to lifting would increase levels of ABA in the bulb and through the interaction with ABA lead to improved storability.

Sprout growth in bulbs varied between experiments with an average sprout length after 6 months cold storage of cured onions of 2.16 cm and 1.11 cm for the WW control treatment of HortOnion01 and HortOnion02, respectively (Table 13).

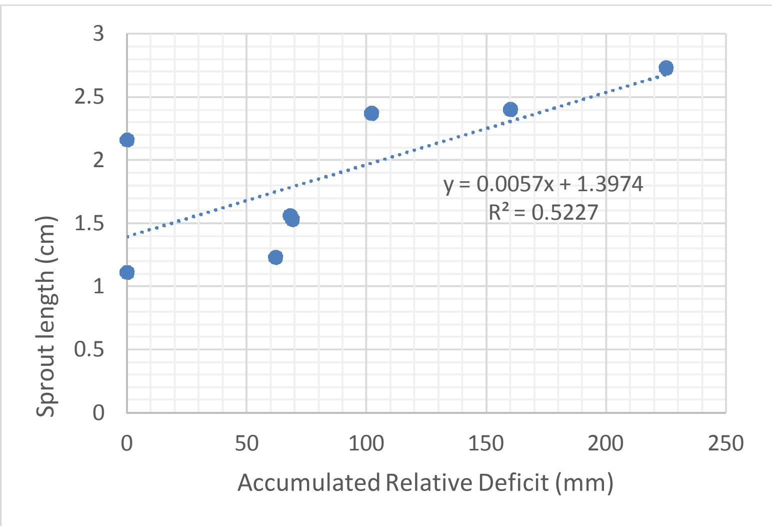
Table 13 *Extent and timing of deficit, accumulated relative deficit during treatment, pinking score at day 20 and derived relative pinking imposed during deficit treatments for the experiments that address Objective 2.3.*

Experiment	Duration of deficit	Week number	Sprout growth after 6 months (cm)	Accumulated relative deficit during treatment (mm)
HortOnion01	-	**WW**	**2.16**	**0**
	9	Wet (11-19)	2.37	102
	9	Mod (11-19)	2.40	160
	9	Dry (11-19)	2.73	225
HortOnion02	-	**WW**	**1.11**	**0**
	9	8-16	1.53	69
	9	8-13 & 17-19	1.23	62
	8	8-13 & 17-18	1.56	68

5.5.2.2 Effect of deficit on post-harvest sprouting in onion

There was no significant effect of treatment on sprout length after 3 months or 6 months cold storage of cured bulbs in either experiment. The least sprouting was observed in the WW treatments in both experiments suggesting that sprouting may be increased with deficit treatments (Figure 1).

Figure 32 *Relationship between accumulated relative deficit during treatment and post-harvest sprouting in cold stored cured onions.*



- No significant response of post-harvest quality to deficit imposed during growth;
- Indication that deficit increases sprouting and reduces storability.

5.6 Conclusions

From a practical perspective, it is more difficult to impose early deficits as the ET levels of young plants, especially onions, is low.

Lettuce

- Imposing a deficit irrigation regime on lettuce will lead to a yield reduction regardless of timing;
- The size of the deficit correlates with final yield;
- The yield loss per mm of deficit increases as the crop develops, and;
- <u>Variable irrigation should aim to maintain SMD close to 0 mm for maximum yield;</u>
- Early deficits have little effect on pinking;
- Mid and late deficits have similar potential to reduce pinking in a crop; and,
- <u>Deficits imposed from mid growth can reduce subsequent pinking.</u>

Onion

- Imposing a deficit irrigation regime on onion will lead to a yield reduction through leaf loss and/or reduced leaf growth in early deficits or reduced bulb expansion in late deficits;
- Early deficits (leaf 7-9) reduce green leaf and total leaf number;
- Reduced green leaf number is associated with a reduced number of bulb scales,
- Late deficits reduce yield more during the early rather than later stages of bulb filling;
- <u>Variable irrigation should aim to maintain SMD close to 0 mm for maximum yield;</u>
- No significant response of post-harvest quality to deficit imposed during growth; and,
- Indication that deficit increases sprouting and reduces storability.

6. Engineering precision irrigation (Objective 3)

6.1 Hypothesis and approaches developed

A precision irrigation system that can vary water application to match varying need, caused for example, by changes in soil or topography, or due to sequential crop production patterns, will deliver improvements in water (and energy) efficiency and crop uniformity.

Overhead irrigation technologies (booms and sprinklers) used in the UK currently fail to apply the same depth of water across a field in a uniform way, with adverse impacts on crop yield and quality (Lacey, 2007). Sprinkler systems are affected by pressure variation along and between laterals and due to ground slopes, inadequate overlap of the application patterns between sprinklers and wind distortion (Musa, 1988; Al-Naeem, 1993). Hosereel systems fitted with guns (which account for most irrigation in the UK) are notoriously susceptible to wind. Hosereel systems using booms (increasingly popular for field-scale horticultural irrigation) are better than guns but still give non-uniformity due to pressure variation, inconsistent pull-in speed and wind distortion. None of the systems currently in use by field scale vegetable growers provide sufficient flexibility to cope with spatially varying water demand, for example, due to sequential planting and/or soil variation.

The focus of this objective was to test and develop prototype irrigation technologies that would allow for more accurate, spatially variable water applications to be made. These could in the future then be linked to intelligent information from planting records, soil maps and/or wireless soil moisture sensing arrays to improve water and energy efficiency. The research for this objective was based on an experimental field site at Cranfield University and system performance evaluation on grower sites. Field and experimental data were then used to calibrate a ballistic model for use in hydraulic modelling and integrated model assessment (Objective 4). The research focussed on two specific tasks addressing variable rate irrigation on sprinklers and booms). The approaches and key findings are summarised below.

6.2 Engineer and test individually valved solid-set sprinklers (T3.1)

6.2.1 Fieldwork and modelling

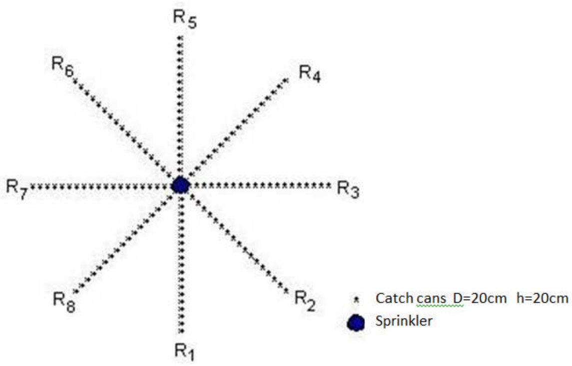
Many growers are now re-considering sprinkler systems as an alternative to drip irrigation, using semi-permanent (seasonal) solid set systems rather than the older conventional portable systems that are moved around the field manually after each application. Sprinklers can provide smaller drops and greater uniformity than rain guns without many of the management and cost problems of trickle irrigation. By combining the technologies for individually-valved sprinklers and computer control originally developed for use in the golf industry with these semi-permanent solid-set sprinkler systems offers potential to produce a cost-effective and highly controllable method of applying water variably across agricultural fields, optimising wetted areas. Optimisation of which sprinklers should operate simultaneously would also allow for smaller pipe sizes and operating pressure, thus reducing capital and running (energy) costs.

The options for installing small hydraulic valves on a sprinkler riser were first evaluated. A solid-set sprinkler irrigation rig (16 sprinklers arranged in a grid) was designed, built and evaluated on a level grass site at Cranfield University (Figure 33). Electronic valves were fitted to each sprinkler in the grid. The valves were powered and controlled using a 2-wire system with electronic decoders fitted to each valve. The feasibility for using remote controlled (wireless) control valves was also investigated. An electric pump was used to supply water from 2 medium sized portable storage tanks on site. Pressure gauges and flow meters were used to monitor system performance during the rig tests. An automatic weather station (5m from the test site) was used to measure and record weather parameters (change in wind speed and direction). The accuracy of the weather stations was 0.1m/s for wind speed and 1^{o} for wind direction. Extensive field evaluations (irrigation performance assessment) were then conducted to assess how individual sprinkler control could be used to improve normal uniformity.

Figure 33 *Sprinkler test rig constructed for variable rate application at Cranfield University, 2012.*

The hydraulic performance of the sprinkler rig operating under both optimal (design pressure) and sub-optimal conditions (low and high pressure, high wind conditions) was evaluated (Figure 34). Extensive field datasets and radial leg data were collected for parameterising and calibrating ballistic models for simulating overlapped water distribution uniformities, for a range of operating conditions.

Figure 34 *Schematic representation and radial leg single sprinkler test, Cranfield University, 2012.*



Following calibration, the models were used to assess the impacts of varying operating pressure, wind conditions (wind speed and direction) and system configuration (changing lateral and sprinkler spacing) on system performance and precipitation (application) rates. The approaches developed on the solid set sprinklers were similarly extended to a hosereel fitted with a boom in 2013 and its performance similarly evaluated.

6.2.2 Key findings

Using field measured water profile data collected from a sprinkler widely used in UK horticulture (R200WF) (Figure 35) it was possible to then use selected ballistic models to overlap the water distribution pattern of adjacent sprinklers and thereby assess system uniformity. This provides a good indication on the likely average depth and uniformity of the water applied for any given sprinkler configuration and operating pressure. Overlapping models have been developed for use in sprinkler system design but also to evaluate the system without the need to conduct excessive field tests. The SUE (Sprinkler Uniformity Evaluation) model (Daccache, 2009) was used in this study to simulate water application volume and irrigation uniformity for different sprinkler spacings (8×8, 10×10, 12×12 and 14×14 m) and at the same operating pressure (350 kPa). By reducing sprinkler spacing, the uniformity of water application improves and the water volume applied per area increases. However, the capital cost of such a system would also increase dramatically as more sprinklers per unit area are required. An example of the simulated spatial distribution of water applied is shown in Figure 36 and the uniformity parameters summarised in Table 14.

Figure 35 *Experimental radial leg data collected at Cranfield University to assess the effect of working pressure on water distribution of the R2000WF sprinkler under 'no-wind' conditions.*

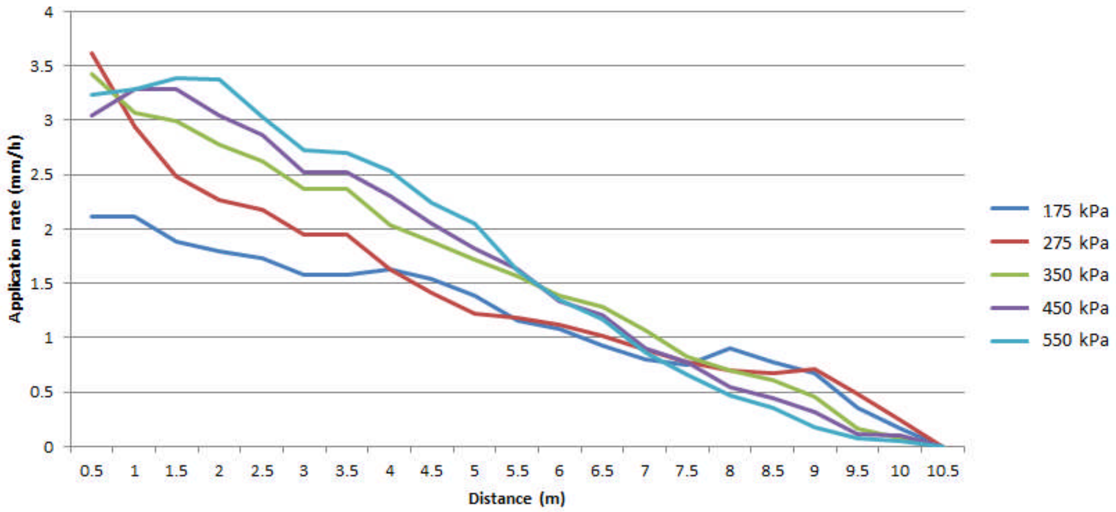


Figure 36 *SUE modelled water distribution pattern for the R2000WF sprinkler operating at 350 kPa at sprinkler distances of (a) 8×8m, (b) 10×10m, (c) 12×12m and (d) 14×14m.*

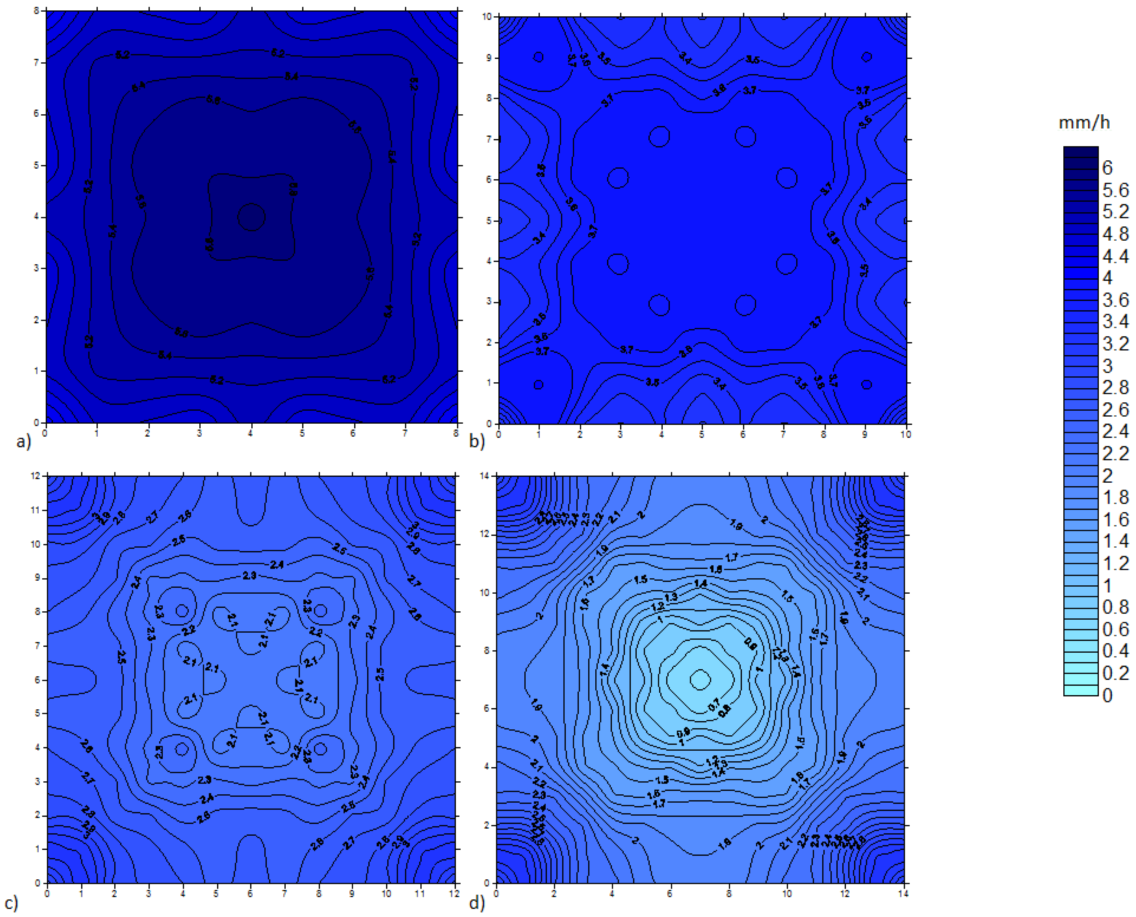


Table 14 *Water distribution uniformity performance data (%) for the R2000WF sprinkler operating at 350 kPa and four different sprinkler spacing (m) distances.*

Sprinkler distance (m)	CU (%)	DU (%)	Mean application rate (mm/h)
8×8	93	87	5.27
10×10	91	85	3.63
12×12	90	81	2.56
14×14	76	60	1.93

A similar analysis was repeated but fixing the sprinkler spacing (12×12m) and varying the operating pressure. The highest uniformity was obtained at an operating pressure of 275 kPa. Such uniformity will noticeably reduce as the sprinkler pressure increases (Table 15).

Table 15 *Performance of the R2000WF sprinkler working at different operating pressures (kPa) and at a 12×12 m sprinkler spacing.*

Pressure (kPa)	CU (%)	DU (%)	Minimum depth of applied water d_{90} (mm/h)
175	92	88	2.26
275	93	89	2.20
350	91	85	2.17
450	87	77	1.90
550	82	68	1.75

6.2.3 Single sprinkler tests under windy conditions

To assess the effects of wind on the observed water distribution patterns, catch cans were arranged in a grid around each sprinkler. The distance (2m) between each catch can was fixed (Figure 37). The outputs from these tests were used to calibrate and validate the SIRIAS model (Carrion *et al*., 2001; Montero *et al*., 2001). The SIRIAS model is a mathematical ballistics model which has been developed for evaluating simulated or measured sprinkler data under both variable sprinkler and weather conditions. The theoretical basis of this model consists of applying ballistic theory to a single droplet to simulate wind drift and hence the sprinkler water profile distortion. A detailed model description is given in Carrion *et al*. (2001)

Figure 37 *Single sprinkler evaluation under windy conditions at Cranfield University (2012).*

Using ballistic theory, the water distribution pattern for a single sprinkler under windy conditions is nearly circular and hence does not accurately reproduce the real distortion caused by wind. Since droplets interfere with each other in the air, it is necessary to introduce a correction coefficient (C') to adjust the simulation to reality (Seginer *et al*., 1991; Tarjuelo *et al*., 1994; Li and Kawano., 1995). This distortion consists of a narrowing in the direction perpendicular to the wind as well as a windward shortening and an even greater leeward lengthening (Von Bernunth and Seginer., 1990). To achieve this deformation, Tarjuelo *et al*. (1994), following Seginer *et al*. (1991), suggested a correction for C air drag coefficient, as a function of the correction coefficient K1 and K2:

$$C' = C(1 + K_1 \sin\beta - K_2 \cos\alpha)$$

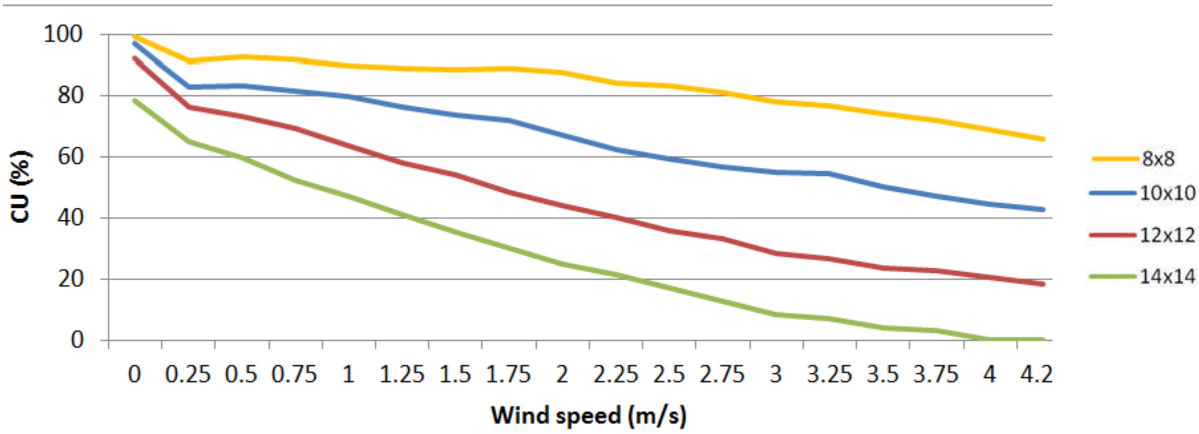
Where:

β: angle formed by vectors V (drop speed in the air) and U (drop speed relative to the soil)

α: angle formed by vectors V and W (wind speed vector)

Hence, the calibration of the SIRIAS model can be made by adjusting the K_1 and K_2 parameters. In this study, K_1 varied between 0 and 4 with an increment of 0.25 while K_2 ranged between 0 and 0.4 with an increment of 0.04. Using a trial and error approach, the measured water profile for each isolated sprinkler test was compared against the 153 simulated water distribution patterns, where each run corresponds to a different combination of K_1 and K_2. SIRIAS has a number of parameters to compare the simulated water distribution pattern with the in-field measured values. Once the values of K1 and K2 for R2000WF were obtained, it was then possible to simulate the performance of the system for any given sprinkler configuration and wind speed. An operation that would be excessively time and energy consuming if performed in field and practically unfeasible since the desired variation in weather parameters (wind speed and direction) cannot be controlled. The observed effect of increasing wind speed on irrigation application uniformity is shown in Figure 38. At high wind speeds and in order to maintain an acceptable uniformity it is necessary to reduce the sprinkler spacing. However, this will increase the volume of water applied and inevitably increase capital (pipe and sprinklers) costs of the system. A balance therefore needs to be struck between minimising the effects of wind and pressure on sprinkler performance, against the economic viability of a system capable of applying water variably with a high degree of control.

Figure 38 *Derived impact of wind speed(m/s) on application uniformity (CU%) for different sprinkler spacing (m).*



Further work will be needed to develop suitable algorithm rules to optimise the switching (control) of sprinklers in response to changing wind/pressure conditions and to operationalise the technology for grower use, but the prototype has been successfully developed and tested.

6.3 Engineer and test variable rate boom technologies (T3.2)

6.3.1 Rationale and approach

By varying the advance or wind-in speed on hose-reel systems, the irrigation quantities applied along the travel lane can be varied. By switching individual sprinklers on the boom on or off, or operating them intermittently, different applications can also be applied along the width of the travel lane. Variable rate irrigation (VRI) can therefore be used to apply water differentially to vary the amount applied both across and down the field depending on in-field heterogeneity, such as soil AWC or other factors (e.g. crop variety, sequential planting, field obstructions, roadways). This task focussed on identifying and testing suitable technologies for implementing VRI on a hose-reel fitted with a boom and the broader challenges associated with managing VRI in UK field-scale cropping. By understanding VRI and assessing the technology to apply water more uniformly or variably to match a pre-determined pattern, the task outputs helped to inform Objective 4 (system integration).

In this project, a commercial Briggs hosereel fitted with a small boom was adapted to incorporate wireless controlled solenoid valves fitted to each sprinkler. The four wheeled steel chassis was fitted with 13 sprinklers each 2.5 m apart and fixed 1.5 m above ground level. Each sprinkler was modified with a solenoid valve, itself controlled centrally via a wireless radio link. The system was field tested under different operating pressures and wind conditions. This prototype VRI boom demonstrated that VRI with individually controlled sprinklers is technically feasible. The solenoid valves were successfully tested to pulse at 5 second intervals. However, the main challenge to be overcome relates to the drive mechanism on the hose reel. Most UK systems use through-flow turbines to drive the reel, taking some of the energy from the water before it travels along the hose to the boom. This imposes a minimum flow rate before the turbine stalls and pull-in ceases. Typically no more than half the nozzles could therefore be closed simultaneously. Furthermore, a change in flow will alter the pull-in speed. For commercialisation, the reel would need to be fitted with a speed controller or separate power source to control the wind in speed irrespective of flow rate through the turbine. The discharge variation caused by VRI would necessitate use of a variable frequency drive to maintain pump operation at the desired efficiency. This would ensure that any pressure fluctuation at each sprinkler is minimized. It should be noted that pressure will affect not only the volume of water applied but also the droplet size distribution from the sprinkler. At high pressure the water jet will disintegrate faster into smaller drops that can easily drift by wind. Conversely, larger water droplets created by low pressure would increase the risk of crop and soil damage.

6.3.2 Factors influencing irrigation system performance

The irrigation market has many sprinklers of different shapes and design. The one most widely adopted for UK booms are rotating plate sprinklers. Two Nelson 3000 sprinklers with the same nozzle size (#36) and deflecting plates but with different caps were tested at Cranfield University. The rotating speed of the plate depends on the type of cap used - it rotates with the blue cap (R3000) and spins with the grey cap (S3000). The mini-boom adapted for VRI was retrofitted with these two types of sprinkler and then modified with individually wireless controlled solenoid valves to test VRI technology for switching each sprinkler on/off. The water distribution patterns for the S3000 and R3000 sprinklers were assessed under different operating pressures and wind speeds. A mobile weather station was used to record changes in wind speed and direction during each field test. The same analyses were also conducted on the original sprinkler (D3000) fitted to the boom. To dynamically simulate the way each sprinkler's water profile changed under varying wind and pressure conditions, a ballistic model was developed and calibrated using the test data. The ballistic model was then integrated into a boom simulation model to evaluate VRI benefits under typical UK conditions. The model was also developed to simulate uniform irrigation (URI) or variable rate irrigation (VRI). The latter achieved through variable pull in speed or using individually controlled sprinklers.

The performance (uniformity and volume of water applied) of an overhead boom irrigation system depends largely on (i) the type and characteristics of the sprinklers used, (ii) the design of the boom structure (height and individual sprinkler spacing), (iii) the pull in speed and pipe sizing, and (iv) ambient hydraulic (pressure) and climatic (wind) conditions during field operation. The pressure at the nozzle can be affected by field topography and load on a single pump when it is used to supply a number of irrigators being operated simultaneously. In recent designs, pressure regulators are used to overcome pressure fluctuations at the nozzle. Note that pressure regulators are effective on high pressures but fail when pressure is too low. In addition, pressure regulators can improve uniformity but can also generate important energy losses in the system and hence lead to higher energy costs.

Wind speed and wind direction are the main factors affecting the uniformity of water distribution from overhead irrigation systems. As these change continuously, the performance of the system fluctuates accordingly. Sprinklers with smaller water drops are more sensitive to wind drift and evaporation. Also, the height of the sprinkler on the boom frame influences how susceptible it is to wind drift (influencing droplet flight). Pressure and wind sensitivity are not isolated factors. The jet of water from a sprinkler operating at a higher pressure disintegrates into smaller drops compared to the same sprinkler operating at a lower pressure, making it more sensitive to wind distortion.

6.3.3 Fieldwork

A flat grass field at Cranfield University was used as an experimental site to perform a series of outdoor sprinkler uniformity tests. A small boom of 16.5 m width equipped with 7 sprinklers at an average height above ground of 1.35 m. This small boom (mini-boom) has been customized for research purpose but similar ones are manufactured to irrigate horse racing tracks and other sport pitches where the large agricultural booms (56-72m width) cannot fit. An electric pump with variable speed drive was used to pump water at any required pressure (1-5 bar) from 2 medium size storage tanks to the sprinkler under test and mounted on the boom. A pressure gauge was installed just before the sprinkler to ensure the uniformity test was conducted at the desired pressure. A flow meter was also installed on the supply side to measure sprinkler discharge at each operating pressure. Limited by pump size and water availability, only one sprinkler at a time was tested with the mini-boom used to provide physical support and appropriate height for the test. Therefore, with each test the pressure at the sprinkler is regulated by the variable speed drive pump and checked using a manometer at the sprinkler level. The water discharged by the sprinkler is also measured by flow meter. During the test, wind speed and direction are continuously measured using a mobile automatic weather station and averaged for each 10 minute period.

6.3.3.1 Assessing sprinkler performance under 'no wind' conditions

Sprinkler water distribution patterns differ from one sprinkler to another depending on the size of the nozzle, type and the design of the sprinkler itself. The distribution pattern of any sprinkler is also affected by operating pressure (Daccache, 2010) and can be largely distorted by wind (Tarjuelo *et al.*, 1999). The first sprinkler tests were conducted on the experimental site under absence (circa) of wind. Most of the experiments were conducted early morning on selected days when wind speed was s negligible. The aim was to measure the water distribution pattern of the sprinklers under test when pressure is the only factor. In this study, the Nelson sprinkler 3000 series was selected for the uniformity test. These are widely used on centre pivot/linear move and boom systems in the UK. The different components of the 3000 series sprinklers (nozzle, plate and cap) are interchangeable and colour coded (Figure 39). In this study, the 3TN nozzle system #36 purple with the blue plate were used but with two different types of caps. The plate rotates slowly with the blue cap (R3000) and spins when the grey cap is used (S3000).

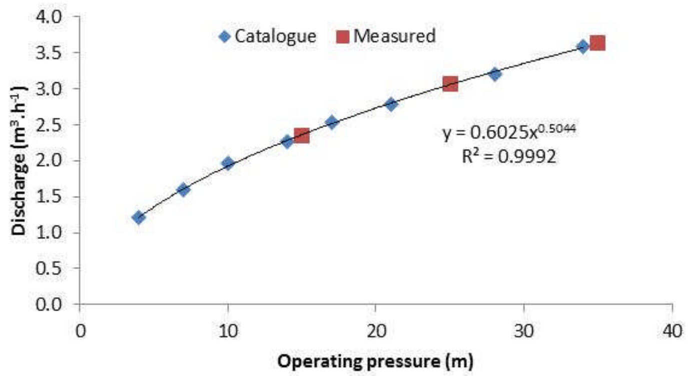
Both the S3000 and R3000 were tested under no wind conditions at 3 different operating pressures (1.5bar, 2.5bar and 3.5 bar). Having the same nozzle size (# 36 purple), the relationship between the sprinkler pressure (*H*) and discharge (*Q*) is the same for both sprinklers (S3000 and R3000) but their water distribution patterns and droplet size might differ since they use different type of plates. The measured pressure-discharge equation (Equ.1) of the 3TN nozzle (#36 purple) was consistent with those published in the manufacturer's catalogue (Figure 40).

$$Q_{(m^3.h^{-1})} = 0.6025.H_{(m)}{}^{0.5} \qquad [1])$$

The rotator (R3000) and spinner (S3000) water distribution patterns were evaluated on a very calm day to minimize wind distortion. Both sprinklers were tested at three different pressures (15m, 25m and 35m) regulated at the pump end and checked on the manometer installed at the nozzle end.

Figure 39 *Main components of Nelson's 3000 series sprinklers*

Figure 40 *Relationship between pressure and discharge for the 3TN Nelson nozzle (#36 purple) from measured and published (manufacturer) values.*



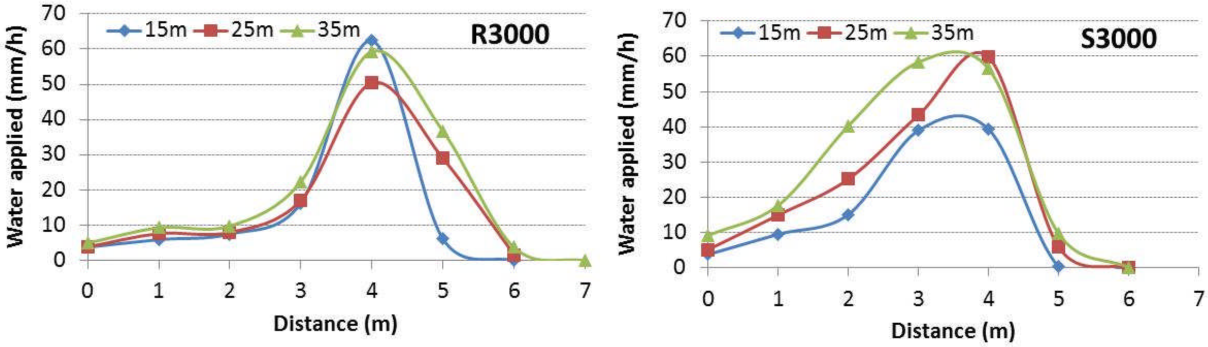
To measure the water distribution profile of the S3000 and R3000 sprinklers in the absence of wind, catch cans were arranged in 8 radial legs around the sprinkler (Figure 41). The length of each radius was 7m (based on the maximum wetted radius) and the distance between cans fixed to 1 m. As wind is not an issue in these tests, each radii is a replication of the measured radial curve of the tested sprinkler. The effect of pressure on the sprinkler water profile is presented in Figure 42.

Figure 41 *Evaluation tests for (a) Rotator (R3000) and (b) Spinner (S3000) operating at the same pressure (25m) under 'no wind' conditions.*

With the rotator cape (R3000), water from the 3TN nozzle is distributed on a 4 m distance as a ring around the sprinkler. As pressure increases, the width of the water ring extends toward outside (up to 5 and 6 m) and the length of the throw increases. In close proximity to the sprinkler (<3m), the volume of water applied remains the same (or almost) (Figure 42).

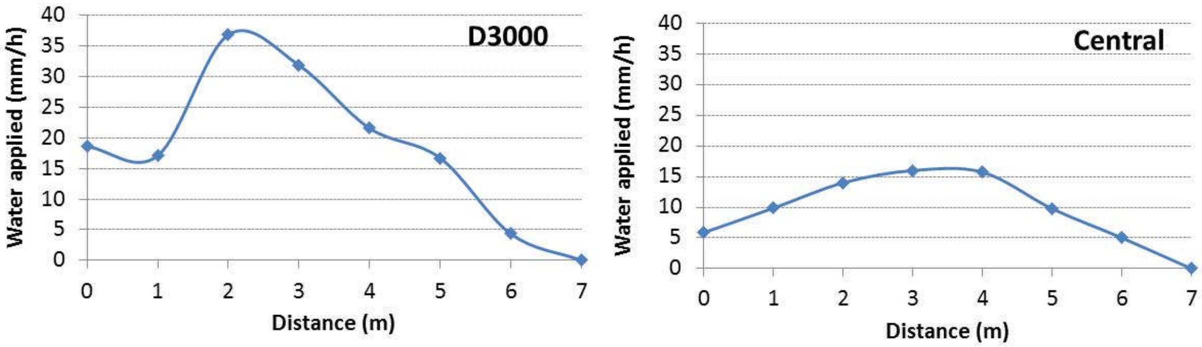
The high velocity of the water reflected on the spinner plates makes the water jet disintegrate quicker into smaller drops. As smaller drops are easily dragged by air, most fall in close proximity to the sprinkler. For that reason, a more uniform water pattern is observed using the spinner cap. At 15m pressure, most water (> 30 mm/h) is applied between 2.5 to 4.5 m from the sprinkler. At high pressure (35m) a similar water distribution pattern is observed but with a clear increase in the volume of water applied across the profile (Figure 36). Even though a lighter water pattern is more suitable for sensitive crops and soils, smaller water droplets are more easily drifted by wind.

Figure 42 *Water* profiles of the R3000 and S3000 sprinklers under different operating pressures.



The mini-boom used in this study was originally fitted with 360 degree rotating plate sprinklers (D3000) on the wings and on the boom centre with a fixed deflecting plate with a wetting angle of 180 degree to avoid wetting the soil in front of the advancing boom structure. Also each sprinkler was fitted with pressure regulator to provide a constant operating pressure of 2.0 bar. Uniformity tests were also performed on these sprinklers but due to the pressure regulators, the original boom sprinklers were tested for only one pressure (2.0 bar).

Figure 43 *Water profiles of the original sprinklers used on the mini-boom operating at 20 m pressure.*



6.3.3.2 Assessing sprinkler performance under 'windy' conditions

Wind can distort a sprinkler's water distribution pattern and increase evaporation and drift losses. To test the effect of wind on the sprinkler water distribution pattern, the catch cans in this experiment were arranged in a square grid around the sprinkler with 1m separation distance between the cans (Figure 44). As with the 'no wind' experiments, the duration of each test was set to 30 minutes during which wind speed and direction were continuously (circa) measured using an automatic wireless anemometer and averaged over 10 minute periods. Water distribution patterns of R3000 and S3000 as distorted by wind when operating at different pressures (15, 25 and 35m) are presented in Figure 45 and Figure 46, respectively. The original boom sprinkler (D3000) fitted with 20m pressure regulator was also tested under windy conditions. A summary of the tests conducted and the average wind speed registered during each test are presented in Table 16.

Figure 44 *Evaluation test for a) Rotator (R3000) and b) Spinner (S3000) under windy conditions.*

Table 16 *Summary of the sprinkler tests conducted at different wind speeds and pressure.*

	Sprinkler						
	D3000	***R3000***			***S3000***		
Pressure (m)	20	15	25	35	15	25	35
Wind speed (m/h)	4.3	2.7	3.2	3.2	2.7	1.7	2.2

When the water jet is directed into the wind, air resistance on water drops increases making larger drops unstable with a tendency to disintegrate faster into small drops; these are slowed down by air resistance and blown back toward the sprinkler (in the wind direction). Conversely, a jet of water travelling in the same direction of wind will encounter lower air resistance and drift further. Hence, wind distortion consists of narrowing the sprinkler's water profile in the windward direction and lengthening it in the leeward direction (Von Bernuth and Seginer, 1990). Rather than having a circular water distribution pattern (no wind), the sprinkler water pattern under wind conditions is more elliptical with the central of gravity shifted toward the wind direction (Figure 45 and Figure 46).

Figure 45 *R3000 and S3000 sprinklers water distribution profile operating at 3 different pressures under absence and wind conditions.*

R3000	**S3000**

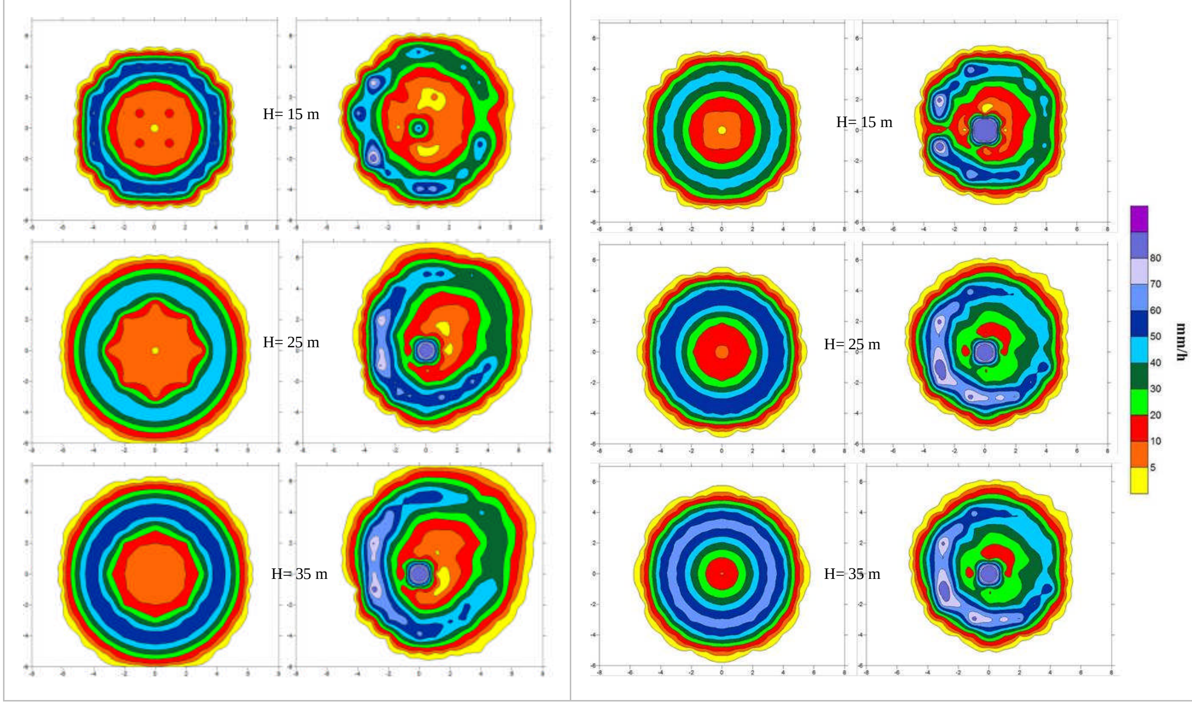
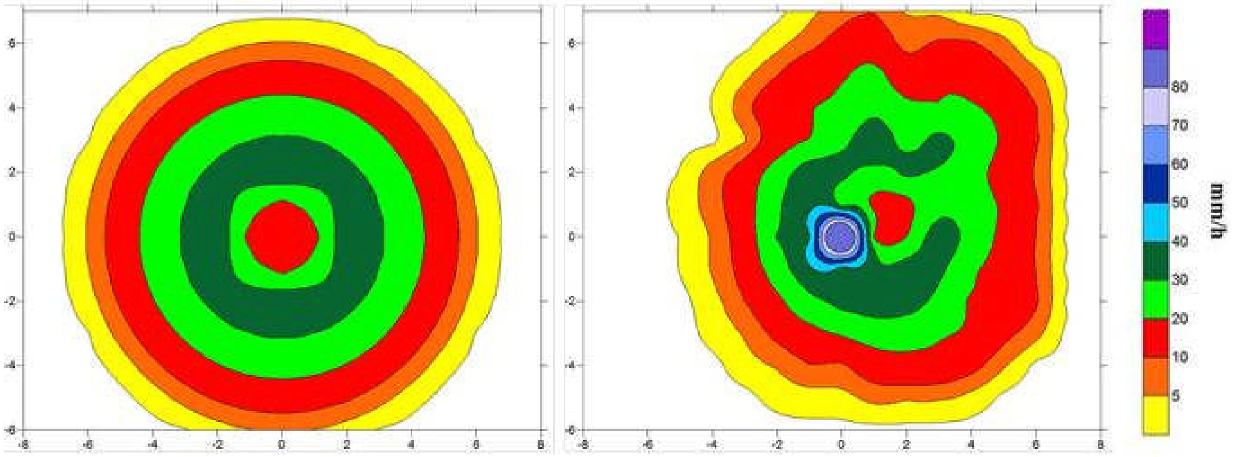


Figure 46 *Water distribution profile of the boom sprinkler (D3000) distorted by wind.*



6.3.3.3 Developing a ballistic model for wind simulation

The use of the ballistics method to simulate wind distortion of a sprinkler water profile was first introduced by Fukui *et al.* (1980). Subsequently, further improvements to the ballistic method were made by Vorries *et al.* (1987) and Seginer *et al.* (1991). More recently, a complete ballistic model (SIRIAS) for sprinkler simulation under wind conditions was presented by Carrion *et al.* (2001). The SIRIAS model has been used by many researchers and calibrated for a large number of sprinklers (Montero *et al.*, 2001; Playan *et al.*, 2006). The ballistic model assumes that droplets are formed at the sprinkler nozzle then travel independently (drops do not fuse or disintegrate) until they reach the soil or crop canopy surface. In the absence of wind, the trajectory of each drop is subjected to (i) initial velocity of the drop at the nozzle end (U_0) which is pressure and plate design (in case of rotating or fixed plate sprinkler) dependent, (ii) gravity force in the vertical direction and (iii) to a resistance force (F_R), which opposes the relative movement of the drop in the air (Vories *et al*., 1987; Seginer *et al*., 1991) (Figure 47). The air resistance force (F_R) on an isolated drop is expressed as:

$$F_R = \frac{1}{8}\rho_a C \pi D^2 V^2 \qquad [2]$$

Where *V* is velocity of the drop in the air; ρ_a is the air density; *D* the water drop diameter and *C* is the drag coefficient for an isolated drop and is function of the Reynolds' number (Re). Under windy conditions, the drop velocity with respect to the ground (U) is equal to the drop velocity respect to the air (V) plus the wind vector (W) that represent wind speed and direction (Figure 47). The new forces acting on a single drop and defining the drop movement can be summarized as:

$$\Sigma F = m\frac{dU}{dt} \qquad [3]$$

Accordingly the three directional accelerations of the drop movement in the air can be expressed as:

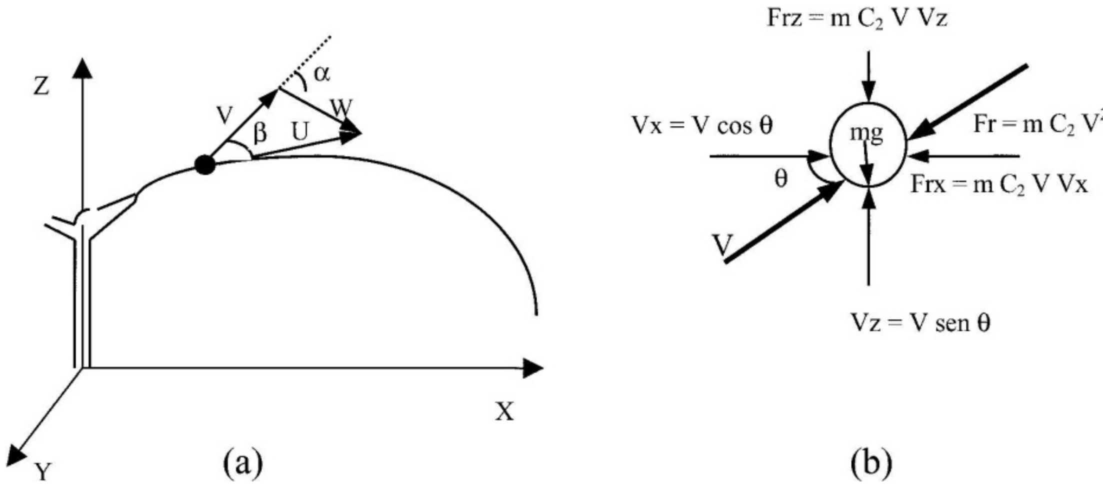
$$A_x = \frac{d^2x}{dt^2} = -\frac{3\rho_a C}{4\rho_w D}V\left(\frac{dx}{dt} - W_x\right) \qquad [4]$$

$$A_y = \frac{d^2y}{dt^2} = -\frac{3\rho_a C}{4\rho_w D}V\left(\frac{dy}{dt} - W_y\right) \qquad [5]$$

$$A_z = \frac{d^2z}{dt^2} = -\frac{3\rho_a C}{4\rho_w D}V\left(\frac{dz}{dt} - g\right) \qquad [6]$$

Where: x, y, z are coordinates referring to the ground (with origin at the sprinkler nozzle); ρ_w the water density; while dx/dt, dy/dt, dz/dt are components of drop velocity (U).

Figure 47 *A two-dimensional schematic showing a water droplet moving through air and the forces that act upon it (Carriòn et al., 2001).*



Using ballistic theory, in the absence of wind and the measured water profile of the sprinkler under study, it is possible to associate at each distance from the sprinkler the droplet diameter size and the corresponding volume of water applied. Under windy conditions, the wind speed and direction will determine the new landing location for each droplet and it is associated water volume.

6.3.3.4 Ballistic model calibration

A ballistic model to simulate wind distortion of S3000 and R3000 water patterns has been developed based on the mathematical approaches described above. The distorted pattern using the ballistic approach is nearly circular but in reality consists of narrowing of the water profile in the cross wind direction, shortening it windward and lengthening it leeward. To achieve this deformation, Tarjuelo *et al.* (1994) introduced two coefficients (termed K_1 and K_2) to the C air drag coefficient as following:

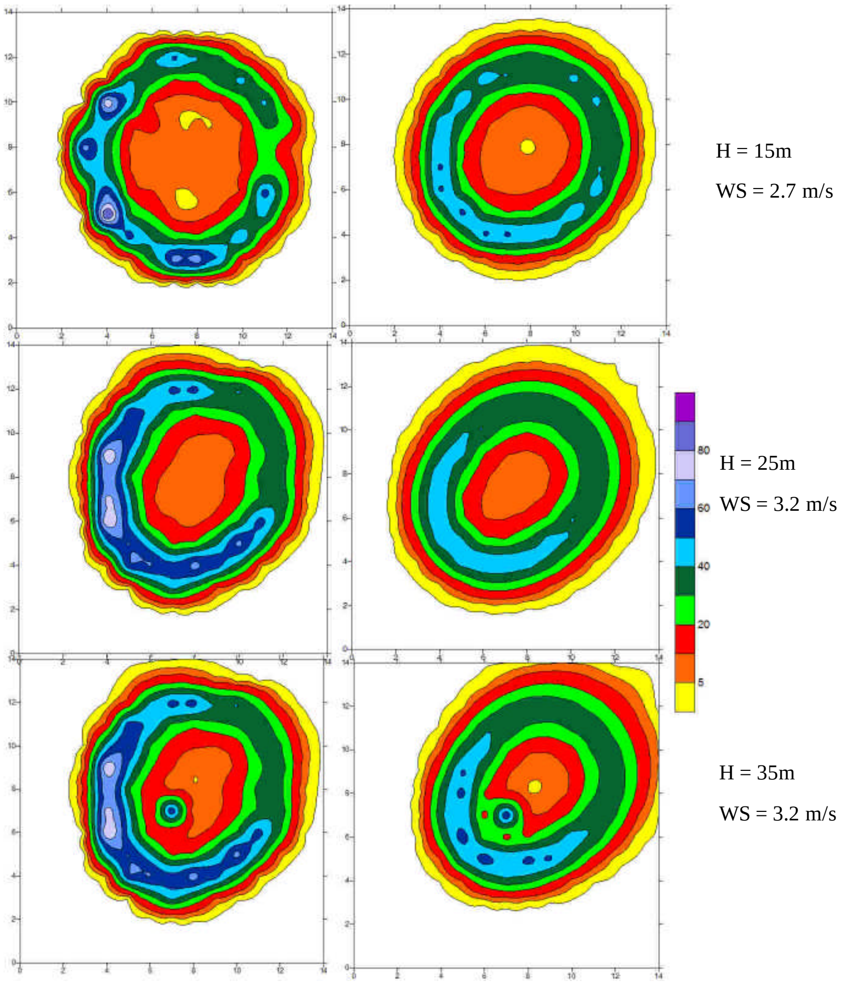
$$C' = C(1 + k_1.\sin\beta - K_2.\cos\alpha) \qquad [7]$$

Where α is the angle formed by vectors V and W; β is the angle formed by vectors V and U. In summary, K_1 factor shortens the pattern in the direction perpendicular to the wind, but less so in the wind direction. K_2 instead is a windward shortening and leeward lengthening factor and without any effect on the perpendicular direction of the wind.

These correction coefficients were estimated and used to calibrate the ballistic simulation model to achieve a good fit between the simulated water applied and the observed field measurements.

A comparison between the measured and simulated water profiles for the R3000 sprinkler operating at 15, 25 and 35m pressure are summarised in Figure 48. The differences between the simulated and measured data is attributed to the estimations used in the ballistic model such as how the jet disintegrates into droplets of different sizes that do not fuse or disintegrate further. The other limitation is the fact that the wind speed and direction is assumed to be on average the same but in reality it is continuously changing; this explains the uneven distortion of the measured patterns.

Figure 48 *Observed and simulated sprinkler (R3000) water distribution profiles distorted by wind at different wind speeds (2.7 and 3.2 m/s) and pressure (15, 25 and 35 m).*



6.4 Conceptualising precision irrigation for agricultural modelling

Despite these differences in interpretation, there is one common aspect to all PI definitions, which is the 'differential' component - both in terms of recognising the need for variable irrigation need across a field and then delivering the variable application of irrigation (Smith *et al*., 2010). PI thus focuses on individual plants or small quasi-homogenous areas within a field, while conventional irrigation management assumes a whole-field approach aiming to apply water as uniformly as possible across the field.

Not surprisingly, most PI definitions and studies in the scientific literature have focussed on 'variable rate irrigation' (VRI), now commonly used on pressurized overhead systems (including centre pivot or linear move systems) which apply water variably in response to feedbacks from spatial information delineating areas reflecting different stages of crop development or drought stress, soil type, topography or land use (e.g. El Nahry *et al*., 2004). However, it is important to recognise that VRI technology represents only one aspect of PI and there are other ways to manage and implement precision irrigation.

The concept of PI proposed by Smith and Baillie (2009) also includes adaptive control, implying that an irrigation system can be managed to achieve a multiple set of objectives, whether it be maximising water use efficiency, maximising crop yield and quality or farm profitability. This requires a modelling approach that can cope with large multiple datasets on water application, possibly at high resolution, simulate crop responses at a scale that reflects the approaches for field management, and then be used to evaluate decision-making strategies to improve irrigation management. For example, through model simulation, spatial changes in soil moisture and crop response could be modelled and validated against in-situ or direct field measurement, and the data then used as a feedback to determine the timing and spatial amounts needed for irrigation (Smith *et al*., 2010). From this, it is evident there are a number of issues that are fundamental to the need to spatially model precision irrigation:

1. The requirement for water will vary spatially due to spatial differences in soil, crop development and micro-climate;
2. The scale of spatial variability may be very small in heterogeneous fields;
3. In-situ soil moisture monitoring is necessarily limited by cost and practicality to a very few points within a field, so, there is a need to model water distribution to be able to estimate what is happening at a sufficiently fine spatial resolution;
4. Financially optimum water application depends on final crop yield and quality which has to be extrapolated from the current condition, and;
5. Water distribution cannot be controlled precisely. Current overhead irrigation systems cannot apply water differentially to a high degree of accuracy because they rely on overlapped wetting patterns to deliver high uniformity. Distribution from overhead systems is also affected by variable wind and operating pressure, and there is a need to optimise equipment performance and energy use in conjunction with water application.

Finally, it is worth briefly highlighting why PI has been ignored within the modelling domain of precision agriculture. In a comprehensive review by Zhang *et al* (2002), the spatial and temporal effects of 'irrigation pattern' on crop production were lumped within 'management variables' along with tillage, fertiliser management, seed rates and crop rotation. This is likely due to the spatial and temporal complexity that exists with irrigation and the confounding effects that spatial and temporal variabilities in soils, agroclimate and nutrient management can have on irrigation management and hence crop yield. The lack of mathematical models capable of simulating the spatial distribution of irrigation water (without extensive model calibration) and the costs of integrated model development are inevitably contributory factors. Indeed, the lack of such a Decision Support System (DSS) was identified by Smith *et al* (2010) as being the most likely factor that has delayed significant commercial application of precision irrigation.

6.4.1 State of the art in biophysical and ballistics modelling

Crop growth models

With careful calibration, crop simulation models provide reasonable estimates of potential yield for a given situation based on the wide range of physiological relationships that govern plant growth and development (Cassman, 2008). The development and application of crop growth models for agricultural decision support is a mature and well established research domain. A relatively limited number of such models now dominate agricultural applications research, with the most widely used being the Decision Support System for Agrotechnology Transfer (DSSAT) program (Jones *et al*., 2003). The diversity in application for DSSAT and other such crop models is undoubtedly due to the significant international interest in climate change impacts on crop production (White *et al.,* 2011). Such models can help simulate the integrating effects of soils, weather, crop management, genetics, and pests on plant growth, and can be used to gain some (albeit still limited) insight into spatial land and crop management variability (Thorp *et al*., 2008). The majority of crop models were, however, developed for use in simulating crop growth and development for a single, homogenous field unit, and lack operational flexibility for use in evaluating precision agriculture, where multiple units or management zones with a single field need to be simulated. Of course, this can be overcome by running such models in batch mode defining each different management unit as an individual point, but this is cumbersome and inelegant from a modelling perspective, and later constrains any attempt to import data into a GIS for spatial analysis.

Thorp *et al* (2008) highlight the limitations of such models and the need for additional procedures to simulate crop growth spatially across management zones at the field-scale. This is especially pertinent given the increasing availability of high resolution and often frequent time-step data emerging from the widespread uptake of information technologies and remote sensing in agriculture (Thenkabail *et al*., 2012). Their solution - a prototype precision farming DSS termed Apollo - represents a major development in functionality for crop simulation in precision agriculture. Although Apollo has been used for evaluating precision nitrogen management strategies (Thorp *et al*., 2006) and to some extent spatially variable-irrigation (DeJonge *et al*., 2007), the approaches for dealing with spatial heterogeneity in water application are still limited. This may not necessarily be a problem when modelling regional level impacts, but does represent a major limitation at the field-scale. Other integrated models suffer similar constraints, particularly in evaluating sub field-level irrigation wetted patterns and their spatial impacts on crop development.

Irrigation water distribution models

As with biophysical models, progress in the development of mathematical models to simulate irrigation water distribution patterns has been strongly influenced by the rapid increases in computing power over the last two decades. Two main modelling methods have been adopted; firstly, empirical or semi-empirical approaches, involving extrapolation from measured water distribution pattern data for various wind conditions (speed and direction) for a defined irrigation sprinkler nozzle, pressure and trajectory angle, and, secondly, deterministic type models, which apply ballistic theory to calculate the flight trajectories of individual water droplets, taking into account their size, velocity and atmospheric effects on the break-up of the jet (Smith *et al*., 2008). Most recent studies for simulating large sprinklers (rainguns) have relied on a semi-empirical model - developed by Richards and Weatherhead (1993) and refined by Al-Naeem (1993) - to predict the distortion by wind on application patterns from an overhead irrigation system (hosereel with a travelling raingun, as used widely in northern Europe and Australia). For these large sprinklers / rainguns, the jet of water entrains a surrounding airflow that carries the water further than a simple ballistic approach (described later) would predict. The water travels in “packets”, with the leading drops slowing due to air resistance and colliding with the following drops which are carried partly by the entrained wind. Cross winds disrupt the entrained wind, shortening the throw. These interactions are not yet susceptible to deterministic modelling and therefore the model uses a complex series of algorithms and empirical parameters to convert a measured ‘no-wind’ pattern into a ‘wind-distorted’ pattern. Field data required for model calibration are either a full-circle pattern or radial leg under still (zero wind) conditions, and two full-circle wind distorted patterns obtained for different wind conditions (Smith *et al*., 2008).

Other researchers started to focus on developing ballistics models for overhead application systems that could be modified and used for precision irrigation. These include fixed (set) sprinkler systems, mobile hosereels fitted with booms and centre pivots (Molle and Gat, 2000); types of system which are all widely used in field-scale agriculture across Europe.

There is a quite separate set of research on small sprinklers, where each drop can be considered independently. The ballistic model used to simulate the effects of wind (speed and direction) on sprinkler irrigation performance was first developed by Fukui *et al*. (1980). This was then developed and improved by researchers including Von Bernuth and Gilley (1984), Vories *et al.* (1987), Von Bernuth (1988), Seginer *et al*. (1991), Han *et al*. (1994) and Tarjuelo *et al*. (1994). More recently, the SIRIAS model developed by Carriòn *et al*. (2001) probably represents the most complete computational software for simulating the trajectory of water droplets discharged by a single sprinkler. It has been calibrated for a large number of manufactured sprinkler types and is designed to simulate the wetted patterns under different wind conditions and nozzle configurations (Montero *et al*., 2001; Playan *et al*., 2006). The ballistic theory assumes that droplets are formed at the sprinkler nozzle and travel independently (droplets do not fuse or disintegrate) until they reach the soil or crop canopy. They also assume that each droplet can be modelled independently, ignoring any entrained wind effects and droplet collisions and break-up during flight. In the absence of wind, the trajectory of each droplet is subjected to the initial velocity of the droplet at the nozzle, a gravity force in the vertical direction and a resistance force, which opposes the relative movement of the droplet in the air (Vories *et al*., 1987; Seginer *et al*., 1991). Under windy conditions, the droplet velocity with respect to the ground is equal to the droplet velocity with respect to the air plus the wind vector.

The water distribution pattern for a single sprinkler operating under no wind conditions and obtained using this procedure is circular. However, in reality, wind distortion consists of a narrowing of the water profile in the perpendicular direction to the wind, and shortening windward and lengthening of the profile in the leeward direction (von Bernuth and Seginer, 1990). To achieve this deformation, Tarjuelo *et al*. (1994) introduced two correction coefficients to the air drag coefficient. These coefficients are fundamental to achieving a good fit between simulated sprinkler profiles and field (observed) measurements. However, the main limitation of the SIRIAS model is that it simulates the performance of only a single sprinkler under a well-defined operating (pressure and wind) conditions. It does not provide scope for analysing the performance of an entire sprinkler irrigation system operating under dynamic conditions where both the operating pressure and ambient wind conditions (wind speed and direction) are continuously changing, which reflects actual field practice. The SIRIAS model also works independently as a standalone ballistic model, and cannot therefore currently be used in conjunction with a crop growth model to assess the impacts of irrigation heterogeneity on crop yield.

Despite the significant research effort made in developing such models over the last two decades, there is a surprising lack of published studies describing their application for assessing irrigation heterogeneity to impacts on crop production. Ruelle *et al* (2003) integrated a semi-empirical modelling approach with the STICS crop model to assess the impacts of irrigation heterogeneity on maize yield and nitrate leaching risks in shallow soils in France. In Australia, Smith *et al*. (2008) developed a DSS for evaluating the performance of overhead irrigation in the sugarcane and horticultural sectors using a crop model and the Richards and Weatherhead (1993) approach for simulating water application. Whilst both considered the effects of irrigation heterogeneity on crop yield at the field-scale they focussed on simulating irrigation performance for equipment (a hosereel fitted with a raingun) that could not easily be managed according to principles of 'precision irrigation'.

6.4.2 Framework for modelling overhead PI impacts on yield

As part of a broader research study investigating the potential for precision irrigation in UK field-scale horticulture, the authors have developed a framework for integrating a deterministic ballistic irrigation model with a biophysical crop model to simulate the impacts of irrigation heterogeneity on crop growth and yield at the field-scale. The approach allows comparison of conventional irrigation management versus alternative precision irrigation strategies, and provides a framework for evaluating the agronomic (yield), water resource (irrigation use and water efficiency), energy (use, cost, footprint) and environmental (nitrate leaching, drainage) impacts for a range of different equipment and management scenarios. It also provides the potential for including feedback loops into defining the management zones and required application depths for the next scheduled irrigation. The approach has been developed for supplemental irrigation using a mobile hosereel fitted with a boom on high value outdoor field-scale crops in a temperate climate, but it could readily be adopted for use on other crop production systems and agroclimatic conditions.

The framework consists of two components, or modules; an irrigation system module, and a crop yield module. By 'irrigation system' we refer to the combined engineering, hydraulic and management components that are necessary to apply water via an overhead irrigation system. A brief description of each, including the input datasets, and modelling architecture for data integration, together with sample output, is given below.

Irrigation system module

The irrigation system module combines data and information on field management units, the engineering hydraulics and characteristics of the irrigation system and ambient short-term changes in local weather conditions to dynamically simulate the performance of the irrigation system as it moves along the field, generating an overlapped wetted pattern taking into account changes in soil and topography and system operating conditions. It was developed using Microsoft VB.Net and designed as a MapWindow plug-in (Ames, 2007) in order to incorporate a number of spatial datasets and to harness the advantages of GIS mapping functionality. The module contains eight discrete components which are combined to model and map the spatial distribution of water applied onto a crop but affected dynamically by spatial and temporal changes in wind (speed and direction), system operating pressure (as this influences flow rate and hence discharge) and field topography (as this influences operating pressure and wetted patterns). The individual components and their inter-dependencies are shown in Figure 49 and described below.

1. *Sprinkler data*: this includes experimental data relating to the measured water distribution patterns for an individual sprinkler. Data is also required on the height of the sprinkler from the ground (to estimate wetted area), the hydraulic operating characteristics of the sprinkler (design pressure to estimate droplet ballistics), and adjustment coefficients (for ballistic model calibration);

2. *Irrigation system*: this includes information and data relating to the hydraulic and engineering characteristics of the equipment (hosereel fitted with boom) and how it operates under normal conditions, including the number of installed sprinklers and their type, the wetted width for boom (instantaneous wetted area), the operating pressure and details on the reel system hydraulics (pipe diameter and length to calculate pressure head and energy losses;

3. *Geodata*: information describing the configuration of the field in terms of topography (usually from a digital elevation model, DEM), as well as spatial datasets relating to in-field soil variability (usually collected via in-situ soil sampling with electro-magnetic induction (EMI) scanning (e.g. Hedley and Yule, 2009) and delineation of management zones. These need to be large enough to be practically and economically manageable and independent from other field attributes (Dennis and Nell, 2002). The most common techniques used to delineate management zones are based on either (i) historical yield monitoring, (ii) real-time crop water stress sensing (i.e. infra-red thermometer) or (iii) soil mapping, in conjunction with EMI scanning. In some agricultural systems, the importance of sequential planting dates and varietal boundaries for commercial cropping (e.g. salads) is also an important issue for defining management zones. The importance of field topography is that changes in elevation influence the operating pressure and hence the system capacity to provide the correct pressure at the sprinklers, with consequent impacts on the application rate and uniformity;

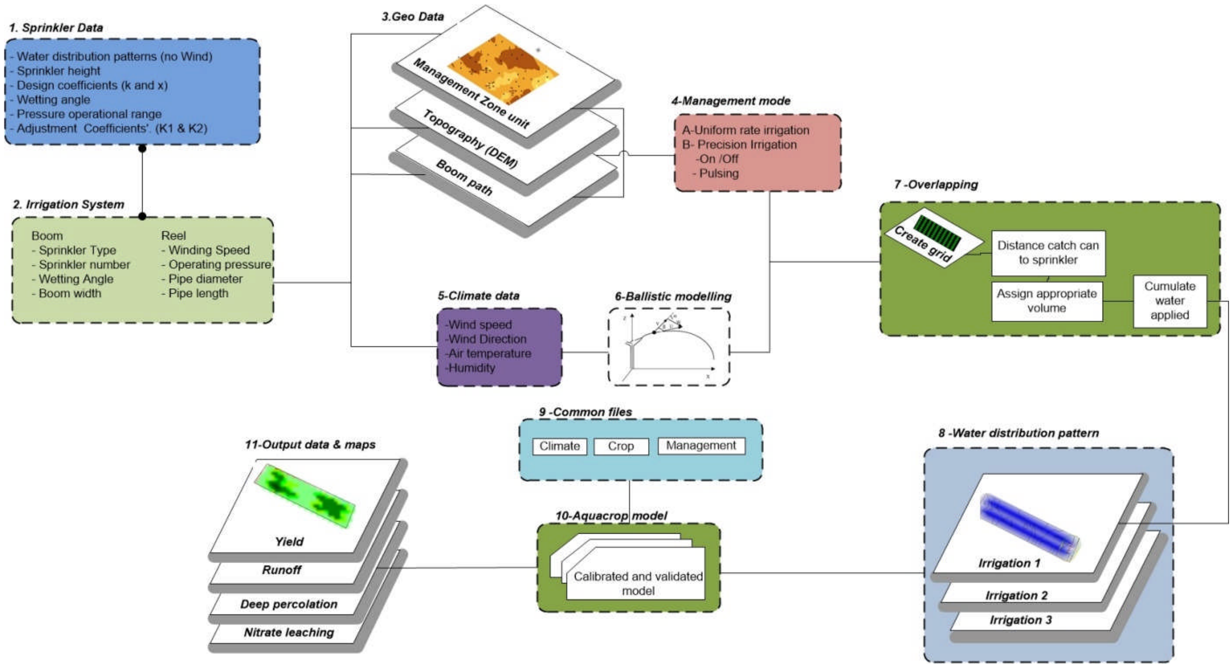
4. *Irrigation management*: Criteria for defining conventional management (schedules for irrigation timing and frequency) or for precision irrigation (including rules for system management, sprinkler pulsing, switching on/off sprinklers in different management zones);

5. *Crop data*: high frequency local climate data for wind speed and direction (usually 15 min interval) and temperature and humidity for input into the ballistics model;

6. *Ballistics modelling*: Application of ballistic theory to simulate irrigation water distribution under no wind and changing wind conditions to generate gridded datasets showing wetted patterns;

7. *Overlapping*: involves algorithms to generate patterns of wetted overlap for each irrigation event, taking into account the direction and speed on the irrigation machine moving along the field, the effects of changing wind, topography, and operating pressure conditions on water distribution.
8. *Water distribution pattern*: Derived gridded datasets for field showing the spatial heterogeneity in irrigation water application, reflecting spatial and temporal changes in weather conditions during the irrigation event, and any changes in operating conditions (pressure) for the equipment.

Figure 49 Schematic showing an integrated approach for combining a ballistic irrigation system model with a crop model (Aquacrop) to assess the agronomic and environmental impacts of precision irrigation.



An example of the output generated by the irrigation performance model is shown in Figure 50, where the simulated water distribution along a field is shown under 'no wind' and 'typical' windy conditions. The ballistic model is then used to simulate the effects of changes in wind speed and direction on the simulated 'no-wind' wetted distribution pattern. The operational mode of each sprinkler is defined to match the irrigation needs in each management zone, to reflect differences in soil type, available moisture and crop development. Using an overlapping algorithm, data and map outputs are generated to show the spatial distribution of water applied during a precision irrigation event as affected by wind, pressure and topography and in response to decision rules regarding specific management zones.

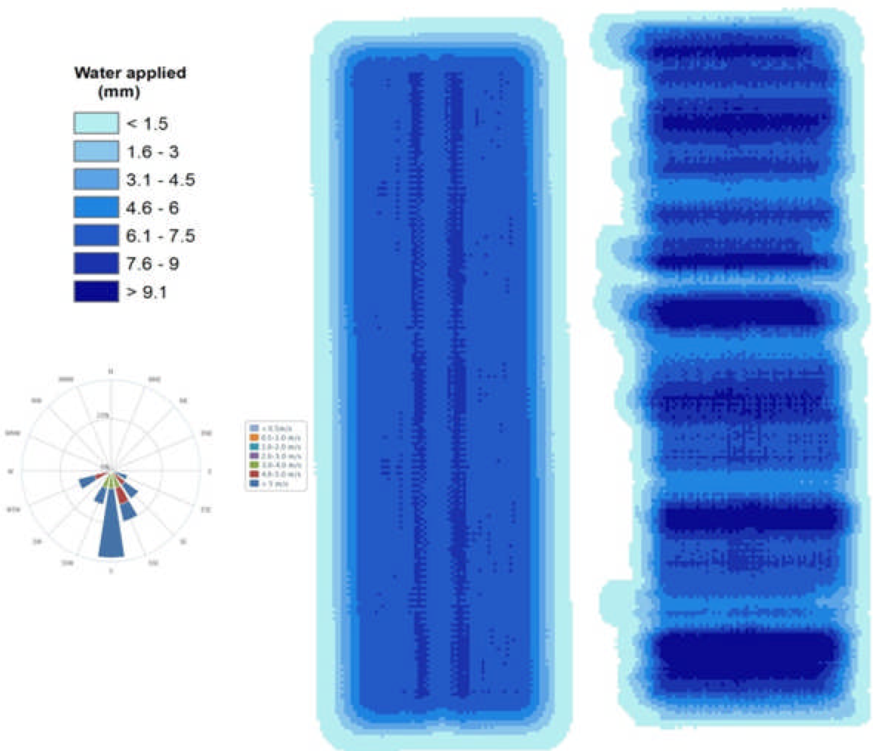
An example is shown in Figure 51 where the irrigation uniformity under a system of conventional irrigation management is compared against a schedule for precision irrigation, where application depths are modified according to management zones. The output data for model runs are exported to the crop module.

Crop yield module

Previous integrated models to assess spatial crop yield impacts have used the DSSAT crop modelling program (e.g. Thorp *et al*., 2010) and STICS model (Ruelle *et al*., 2003). In this study, the Aquacrop model (Raes *et al*., 2009; Steduto *et al*., 2009) was used as it is particularly suited to address production conditions where water is a key limiting factor. The daily soil water balance model is combined with growing degree days (GDD) to predict plant growth stages. Plant development depends on temperature, with biomass accumulation depending on plant transpiration. The Aquacrop model has been used extensively for research purposes, for example, it has been used to predict wheat yield response to different water regimes (Andarzian *et al*., 2011; Salemi *et al*., 2011), rapeseed yield (Zeleke *et al*., 2011) as well as assessing maize, sugar beet and sunflower production under contrasting agroclimatic conditions (Stricevic *et al*., 2011). In this study, the Aquacrop model was calibrated for an onion crop and then validated against experimental and field measurements.

Figure 50 Simulated water distribution pattern from an overhead irrigation system (hosereel fitted with a boom) operating under (a) no wind conditions, and (b) real-time wind conditions (wind rose highlights the wind speed frequency and direction).

(a) (b)

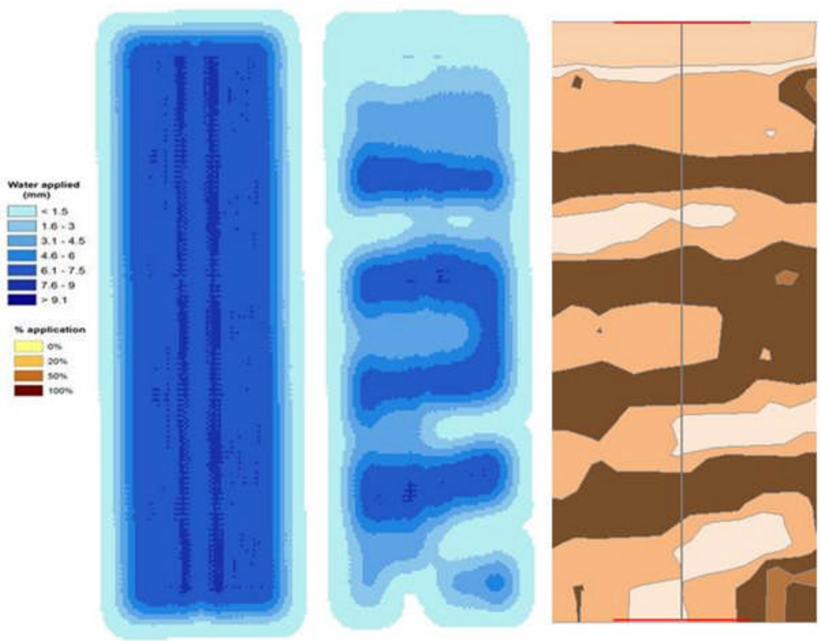


Rather than modelling for single point yield assessment, in this work the model has been linked to the irrigation system module in order to spatially simulate crop growth at a sub-field scale. To do this, the field area was first divided into a gridded mesh based on geodata (soil, topography management zones). It is important to set the grid mesh resolution to a scale that is appropriate for the modelling assessment. For example, modelling of small sprinklers is typically at a 1m grid scale, whereas Richards and Weatherhead (1993) initially used an 8 m grid for collecting raingun pattern data. Spatially gridded data on soil characteristics and the volume of water applied during each irrigation event were then used to simulate crop growth and development (Figure 49). The Aquacrop model can be run in batch mode to simulate crop growth and yield, runoff, deep percolation and crop evapotranspiration. The outputs are generated as a grid file that can then be analysed statistically or imported into a GIS for spatial analysis.

This approach combining the recent mathematical advances in ballistics modelling coupled with biophysical simulation within a framework for precision irrigation assessment on crop yield represents important progress in integrating irrigation ballistics with crop modelling.

Figure 51 Simulated model output for an overhead irrigation system (hosereel fitted with a boom) operating under (a) conventional irrigation management and (b) precision irrigation in response to (c) defined management zones.

(a) (b) (c)



6.4.3 Discussion and concluding remarks

Model application

The approach described here provides a modelling environment and framework for application across a variety of agricultural science disciplines. In addition to assessing the impacts of irrigation heterogeneity on crop yield, the model could be used for, (i) conducting a Monte Carlo type simulation of the impacts of in-field soil variability on yield, (ii) simulating yield impacts of conventional irrigation management versus precision irrigation under a range of contrasting equipment and management scenario, (iii) investigations to assess strategies to minimise nitrate leaching and deep drainage under supplemental irrigation, (iv) evaluate management strategies to make more effective use of rainfall, (v) assess the impacts of conventional and precision irrigation management on water and energy footprints. By incorporating projections of climate change, spatial differences in yield between rain-fed and irrigated production could be evaluated, as well assessing impacts on field-scale irrigation demand, including changes in timing of peak (seasonal) demand and consequences for water and energy management.

Methodological limitations

The approach does, however, have a number of methodological limitations, and scope for further refinement. These challenges include issues such as geodata availability, defining the appropriate scale of model application, ensuring transferability for use with other crop models, and integrating these approaches with current modelling developments in precision agriculture.

Adam *et al* (2012) identify the challenges in coupling different crop models within an integrated modelling framework, both for modellers and end users; many of those issues are also pertinent here. Identifying and selecting the most appropriate scale for conducting the irrigation and crop modelling at the sub-field level is a major issue, and needs to be strongly guided by the intended purpose and application of the output data. The scale of enquiry will also be influenced by the availability, format and resolution of the geodata. The rationale and delineation of management zones or units within a single field also needs to be defined carefully, so that the minimum size suits and does not constrain farm management practices. For example, in the ballistic modelling, the simulation of different wetted patterns for individual management zones needs to take into account the practical feasibility of applying the water, otherwise there is a risk of spatially modelling at a finer scale than is possible using equipment under the assumed farming practices. However, it is important to model at a finer scale than the intended management intervention. The current modelling framework is also only applicable for overhead (spray) irrigation systems, and does not cater for micro (drip) or surface (e.g. furrow) irrigation.

There is also a need for careful documentation of the modelling approaches and particularly how datasets are pre-processed prior to model input, and then how derived datasets are passed between individual models. Great care therefore has to be taken when linking models, as errors in one are propagated to the next. Errors may become exacerbated or attenuated through model integration. There is hence a risk of introducing additional modelling uncertainty, particularly where datasets of different provenance, scale and integrity are integrated. The use of an uncertainty matrix could be used to identify sources of uncertainty both within the irrigation ballistics and crop modelling components, and then used to inform the interpretation of the crop modelling outputs.

Future challenges

The modelling framework described here is being used to assess the agronomic, economic and environmental impacts of different irrigation management strategies (conventional versus precision irrigation) for commercial field-scale onion production in the UK. The approach will then provide a basis for transfer into other high-value horticultural crop sectors where there is an industry and scientific need to understand the impacts of irrigation heterogeneity on crop yield, but more importantly, crop quality, and to identify strategies that can be used to reduce the 'non-beneficial' water losses, to improve water (and energy) use efficiency, and reduce the environmental impacts associated with supplemental irrigation. Integrating biophysical and engineering models to advance our knowledge of these interactions will go some way to addressing these knowledge gaps.

Further work is needed to incorporate suitable economic models to assess the financial impacts of different irrigation management strategies on crop production (to inform discussions on the merits of precision irrigation), to evaluate the use of remote sensed crop cover data for improving crop model calibration, to assess how rapid soil monitoring techniques such as EMI scanning could be used effectively to define soil and irrigation management zones, and finally how integrated modelling frameworks such as this can be used as an effective knowledge transfer tool to highlight the agronomic, water resource and environmental benefits of improved water management in agri-food production.

7. Agronomic and economic impacts of precision irrigation (Objective 4)

7.1 Hypothesis and approaches developed

A precision irrigation system that can vary water application to match varying need, caused for example, by changes in soil or topography, or due to sequential crop production patterns, will deliver improvements in water (and energy) efficiency and crop uniformity. By developing an improved understanding of the links between soil moisture and crop water status and particularly their spatial variability across an irrigated field, we can attempt to (i) quantify the impacts of irrigation heterogeneity on crop productivity (yield), and (ii) the economic viability of investment in precision irrigation. Using data and outputs from Objectives 1 to 3, the research therefore focussed on three key tasks:

(iii) Develop an integrated approach to combine knowledge on spatial soil variability with irrigation performance to define irrigation management zones to assess the hydraulic impacts of precision irrigation;

(iv) Develop an integrated approach to combine knowledge of ballistics and biophysical crop response to assess the agronomic (yield) impacts of precision irrigation, and;

(v) Undertake a financial impact appraisal to assess the economic viability (costs and benefits) of investment in precision irrigation technology and its sensitivity to key variables.

Tasks 2 and 3 used onions as a 'representative' crop for analysis; all tasks relied on extensive datasets collected during the course of the project. The approaches developed were based on combining the experimental and field data within an integrated modelling framework to allow for scenario and sensitivity analysis of variables known to strongly influence precision irrigation. The key approaches and findings are summarised below, but readers interested in more detailed scientific explanation are referred to the following four science publications:

- Perez-Ortola, M., Daccache, A., Hess, T.M., and Knox, J.W (2014) Simulating impacts of irrigation heterogeneity on onion (Allium cepa L.) yield in a humid climate. *Irrigation Science* (in press).
- Daccache, A, Knox, J.W., Weatherhead, E.K., Daneshkhah, A, and Hess, T.M. (2014). Implementing precision irrigation in a humid climate: recent experiences and on-going challenges *Agricultural Water Management* Doi: 10.1016/j.agwat.2014.05.018.
- Knox, J.W., Weatherhead, E.K., Hess, T.M., and Daccache, A (2014) Integrating biophysical and ballistic models to assess agronomic and environmental impacts of precision irrigation. *Environmental Modelling and Software*.
- El Chami D., Knox JW, Daccache A., and Weatherhead, EK (2014) Assessing environmental cost-benefits of precision irrigation using a travelling hose-reel irrigator with a boom in a humid climate – A study in the East of England. *Precision Agriculture* (submitted).

7.2 Defining irrigation management zones of precision irrigation

Traditionally, irrigators have ignored soil and crop variability within an irrigated field (block) and attempted to apply water as uniformly as possible. Indeed, most research efforts have focussed on reducing the impacts of irrigation heterogeneity on crop production. Since soils and crop development are rarely perfectly uniform, this means that under uniform irrigation some parts of the field are implicitly under-irrigated and/or other parts are over-irrigated. PI, in contrast, attempts to apply water non-uniformly to match any required variation in optimum application, for example, in response to soil, crop and/or topographic variability.

The scale, type of production and method of irrigation are all critically important. Here we attempt to provide a critical evaluation of the key technical, agronomic and engineering challenges that still need to be addressed, including the concept of irrigation management zones and how these should be defined to be compatible with existing methods of overhead irrigation. The key questions raised in this section include: (i) are the potential benefits of PI significant, (ii) at what scale does variable rate application need to be developed, and (iii) can mobile hose-reel boom systems apply variable rate irrigation at these scales. Some fundamental differences between conventional and precision irrigation and the links with irrigation scheduling are initially outlined, since this is an important determinant in deciding how PI might be managed. Field data are then used to illustrate the challenges in delineating irrigation management zones (IMZ).

7.2.1 Traditional versus precision irrigation

Traditionally, irrigators have ignored soil and crop variability within an irrigated block and attempted to apply water uniformly across the field. Therefore, unless the soil is also uniform, this means that some parts of the field will be under- or over-irrigated. Under-irrigation impacts on crop yield and quality which in high-value field-scale vegetable production is a key driver for irrigation investment. Under-watering may also lead to increased nitrate leaching after harvest due to in inefficient uptake of nutrients during the growing season (Groves and Bailey, 1997; Bailey and Groves, 1992). Over-watering is, by definition, a waste of water, and therefore energy. However, by keeping parts of the block wetter than necessary during the growing period, there is also an increased risk of drainage and leaching, either from the irrigation itself, or from subsequent rainfall (Shepherd *et al*., 1993). This is particularly important in situations where the soil is kept close to field capacity in the spring (e.g. for scab control on potatoes). In the extreme, over-irrigation can cause waterlogging, with impacts on crop yield, quality and soil trafficability.

In contrast, PI offers the potential to eliminate over-irrigation and apply water in a deliberate non-uniform or variable manner, in response to the specific irrigation requirements of different discrete management units, and hence maximise crop response and minimize any adverse environmental impact (Raine *et al.,* 2005). Rather than regarding the field as a single management unit, under PI management, the field is partitioned into a number of sub-units or irrigation management zones (IMZ). In common with principles of precision agriculture, managing fields as zones is believed to improve efficiency of resource inputs (Moore and Wolcott, 2000). The primary objective of optimising the spatial scale and timing of irrigation applications is therefore intended to increase the crop's biological response (improve yield and quality) to water application whilst simultaneously reducing losses of other inputs (fertiliser). It is not surprising, therefore that most attempts to quantify the agronomic and financial benefits of precision irrigation have focused on arid and semi-arid environments where water availability is becoming increasingly unreliable and expensive, and where irrigation is an essential component of production. However, under humid or temperate conditions, where summer rainfall is an important contributor to crop evapotranspiration needs, the rationale and justification of precision irrigation needs to be carefully evaluated, particularly in the context of potential water and energy savings accrued through adopting a different approach to scheduling.

The combination of mobile irrigators with current approaches to scheduling mean that the whole field block is typically irrigated with the same scheduled depth of water. If soils are uniform, then uniform irrigation across the block to maintain optimum soil water conditions should maximise both yield and quality. However, soils are naturally variable, often over short distances within an irrigated block. Where there are known differences in soil available water capacity (AWC) within a field, it is typical farm practice to schedule the irrigation according to the parts of the field with the lowest AWC in order to ensure that no part of the field is under-irrigated. This is because penalties from under-irrigation are generally perceived by growers to be higher than those associated with over-irrigation. Where growers use in-situ soil moisture sensors to schedule their irrigation, it is common practice to locate these in the parts of the field with lowest AWC and greatest risk of droughtiness (Peters *et al*., 2013). This approach tends to increase the irrigation frequency and lead to more water being applied than necessary to those parts of the block with higher AWC. There is therefore potential to reduce both water and energy use, increase water use efficiency, and reduce leaching of nutrients by using PI to vary irrigation application within a block in response to known spatial differences in soil AWC. In this study we considered the potential savings and benefits from PI for a potato crop grown in England for the fresh pre-pack retail sector (supermarket). Potato cultivation accounts for 43% of the total irrigated area and 54% of irrigation water use in England and Wales (Defra, 2011). Potatoes are grown in geographically diverse locations across England in a range of soil types from sand to clay, although the majority of potato production is on loamy soils. In the wetter parts of the country they can be grown without irrigation, however supplementary irrigation is used in most regions and most years to ensure crop yield and premium quality (Daccache *et al*., 2011).

Three agroclimatic locations were selected to reflect the main potato growing regions in England – Silsoe, Bedfordshire (52.01º N; 0.42º W), Wattisham, Suffolk (52.12º N; 0.93º W) and Shawbury, Shropshire (52.47 ºN; 2.39 ºW) – and three loam soils reflecting high, medium and low AWC, respectively (Table 17). For each soil and climate combination, the seasonal irrigation water requirements (depths applied), water losses (sum of runoff and percolation) and soil moisture deficit (SMD) at harvest were estimated using the WaSim daily soil water balance model (Hess and Counsell, 2000) for the period 1986 to 2011. The weather of each year was characterised by the maximum potential SMD ($PSMD_{max}$) which has been shown to be a useful agroclimatic indicator that is well correlated with irrigation need (Knox *et al.,* 1997). A high $PSMD_{max}$ reflects a year with low summer rainfall and high irrigation need. Irrigation was scheduled using typical irrigation schedules used by potato growers in England. Irrigation of potatoes grown for the pre-packed market in England is as much for quality as yield. Dry soil conditions following tuber initiation increases the risk of common scab (*Streptomyces scabies*), therefore an irrigation schedule was applied to maintain low soil water deficits for scab control (Lapwood *et al*., 1970), with larger deficits allowed thereafter according to AWC (Table 18).

Table 17 *Soil characteristics of each of three AWC classes.*

Available water content (AWC)	High	Medium	Low
Soil type	Loam	Sandy loam	Loamy sand
Saturation (%)	46.3	45.3	43.7
Field capacity (%)	27.9	24.5	16.8
Permanent wilting point (%)	11.7	9.5	5.5

Table 18 *Typical agronomic practices and irrigation scheduling of pre-pack main potato crop in the UK on low, medium and high AWC soils (MAFF, 1982).*

Crop stage	Period	Low AWC	Medium AWC	High AWC
Planting date	1st Apr	-	-	-
Emergence date	5th May	-	-	-
Tuber initiation	30th June	15@ 18 mm	15@ 18 mm	15@ 18 mm
Harvest date	31st August	25@ 30mm	30@55 mm	30@70mm

Seasonal irrigation need is presented in Table 19 for three years selected from each station to represent dry ($PSMD_{max}$ with 10% probability of exceedance), average (50%) and wet (90%) years. These represent the water balance of each soil type under differential irrigation, that is, irrigation of each soil is scheduled according to its AWC. Across the three stations and 26 years, the irrigation requirements of the high AWC soil were 11% less than that of the low AWC soil.

The WaSim model was re-run for each year, assuming that medium and high AWC soils were irrigated at the times and with the amounts scheduled for the low AWC soil. These represent farmers' typical practice in a block with mixed soils, where irrigation is scheduled according to the soils with the lowest AWC. By comparing irrigation applied, water losses and final SMD with the corresponding values for differential irrigation, the potential water saving benefits of PI can be estimated. Table 20 shows that by scheduling the irrigation of the block according the low AWC, on average the medium and high AWC soils are over-irrigated by 18 mm and 22 mm; the additional water losses are 2 mm and 8 mm and the SMD at harvest is reduced by 16 mm and 17 mm, respectively. A lower SMD at harvest means that the soil will return to field capacity earlier in the autumn and drainage will start earlier on the over-irrigated parts of the field. There was no significant difference between the weather stations and no correlation with the year's weather (as expressed by the agroclimatic index, $PSMD_{max}$).

Table 19 *Modelled potato irrigation needs at the study sites in a dry, average and wet year at three locations in England on soils with low, medium and high available water capacity.*

Weather	Site	Year	$PSMD_{max}$ (mm)	Irrigation (mm)		
				Low	Medium	High
Wet	Silsoe	1988	176	120	105	90
	Wattisham	2008	167	135	120	135
	Shawbury	2000	137	95	60	75
Average	Silsoe	1991	310	195	165	150
	Wattisham	1998	271	220	195	180
	Shawbury	1998	240	185	150	165
Dry	Silsoe	1996	462	325	315	285
	Wattisham	1989	433	305	255	270
	Shawbury	1989	370	280	270	240

Table 20 *Additional irrigation applied (mm/yr), increased losses (drainage and runoff) (mm/yr) and reduction in soil moisture deficit (SMD) (mm) at harvest resulting from scheduling all soils according to low AWC.*

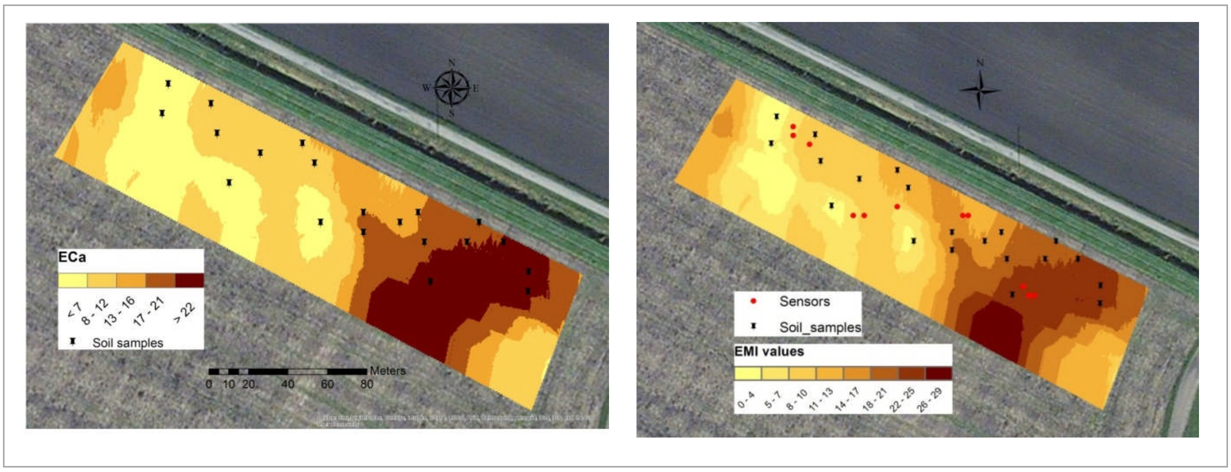
Soil AWC	Station	Additional irrigation, mm/yr	Increased losses, mm/yr	Reduction in SMD at harvest. mm
Medium	Shawbury	20	1	18
	Silsoe	17	3	15
	Wattisham	18	2	15
	Average	**18**	**2**	**16**
High	Shawbury	22	6	19
	Silsoe	21	11	14
	Wattisham	23	8	18
	Average	**22**	**8**	**17**

The simulation above compared farmer practice with optimal irrigation (where patches of different AWC are differentially irrigated). This may be feasible with permanent (fixed) irrigation systems or where the patches of different soil texture are large enough to irrigate at different times. In England, since most irrigation is via overhead mobile irrigators, the entire field needs to be irrigated at the same time, even if the amount applied can be varied spatially. In this case it may be necessary to irrigate parts of the field when they do not need it, in order to ensure that they still have sufficient available water to maintain plant growth until the next irrigation is due. The over-irrigation and losses may then be even higher than indicated above. Given the rotational nature of cropping, PI under supplemental irrigation conditions needs to consider the implications for both scheduling and equipment availability.

7.2.2 Fieldwork and mapping available water capacity (AWC)

Understanding spatial soil variability is therefore a crucial component for PI (Hedley *et al*., 2009). The conventional approach, using soil survey and dense sampling would be the most accurate but analysing a large number of samples is time consuming and a major financial and resource constraint. An alternative approach is to infer soil AWC from soil properties that can be determined from rapid, non-invasive and low-cost electro-magnetic induction (EMI) scanning. As part of a broader study investigating PI in field-scale horticulture, a flat field on a commercial farm in Cambridgeshire (52.47°N, 0.357°E, -2m asl) was chosen to illustrate soil variability and to identify the technical challenges. In-field soil variability was assessed using Geonics EM38 scanner carried by hand and fitted with high accuracy DGPS positioning system. Such technology has been used by other researchers to identify soil variability at field scale (e.g. Hedley *et al*. 2009, James *et al*. 2003) and to inform PI scheduling (Hedley *et al*., 2011). The apparent electrical conductivity (ECa) point data measured by the EMI scanner were interpolated to 1 metre grid to produce the soil (ECa) map (Figure 52). An ordinary kriging method was chosen as it outperformed using RMSE (Root Mean Square Error) other interpolation techniques (e.g. spline, natural neighbour). Similar findings were obtained by Hedley *et al*. (2012) and Robinson and Metternicht (2006).

Figure 52 *Spatial variation measured at the lettuce field site (Cambridge, 2012) using EMI technology. Location of soil sampling points highlighted.*

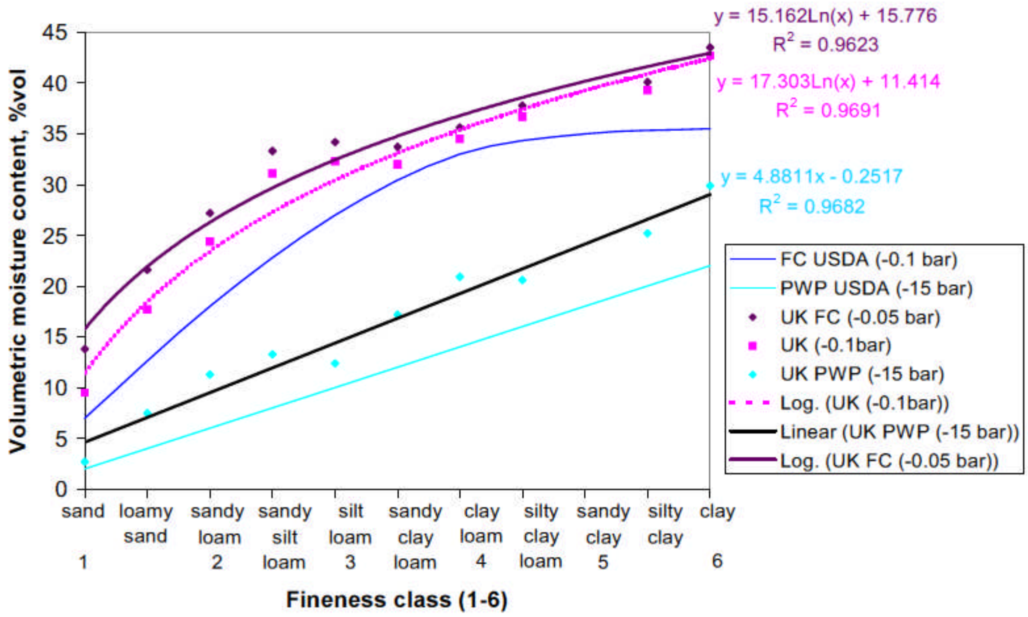


To highlight the challenges of using EMI technology to map soil variability, 20 soil samples were randomly taken from the field for laboratory analysis for particle composition (texture), bulk density and organic carbon content. In humid climates where rainfall exceeds the evapotranspiration (ET), salt build-up is not usually a problem and hence organic matter content, mineralogy, bulk density and soil moisture content are considered the most important factors influencing the measured ECa values (Brevik and Fenton, 2002). Clay and silty clay were the dominant soil textures in the field with an average clay content of 45% (ranging between 37% and 53%) and a bulk density of 0.96 g cm^{-3} (ranging from 0.77 to 1.99 $g.cm^{-3}$). The high organic matter content (18% to 25%) typifies the organic rich fenland soil (drained marshland) in that part of the country. Using linear regression analysis, the highest correlation with the measured ECa at that site was observed with organic matter ($R^2 = 0.71$) and bulk density ($R^2 = 0.65$) and to lower extent with sand (R^2=0.48) and clay ($R^2 = 0.39$) content. This confirmed that the ECa values do not reflect the dominance of a single soil parameter but rather a combination of different factors.

Sensitivity analysis using the variance-based method was then used to further investigate the influence of each soil parameter on the measured ECa values. The variance-based method (Sobol,

1993) was chosen because it is considered the simplest and most effective method (Saltelli, 2002). The variance of the conditional mean (of the input variable of interest) was used as an indicator of how strong the influence of a certain parameter was on model variability. The results showed that the ECa values for this study site were most affected by organic matter content (41% of total variance contribution), followed by silt content (17%) and bulk density (12%). However, the complex interaction between soil variables represented around 20% of the total observed ECa variance. Soil moisture content at field capacity (FC) and permanent wilting point (PWP) were then obtained by using the soil texture fineness index (Waine *et al*., 2000) to identify the location of soil samples on the abscissa of texture-moisture graph (Figure 53). The difference between the FC and PWP curves can be used to determine the AWC of each soil sample.

Figure 53 *UK moisture release curve for typical soils (Waine et al., 2000).*



As with other soil parameters, a poor linear correlation was observed between the ECa values and AWC. Therefore, it is reasonable to suspect that the relationship between ECa and AWC is not linear. According to the scatter plot between these two variables, we can rule out quadratic, cubic, or even a non-polynomial relationship between ECa and AWC. An alternative method is to use the principle of model selection to choose among the various possibilities. Gaussian process regression (GPR) is an even finer approach than this. Using this method rather than assuming a pre-specified model (e.g. linear, quadratic) to be fitted to the data, we can rigorously let the data 'speak' more clearly for itself. GPR is considered a form of supervised learning, but the training data are harnessed in an ingenious way. In other words a Gaussian process model is a data interpolation tool which can be used to infer the relationship between input variable(s) and the corresponding output. The main assumption required to use GPR is that the underlying function of interest is continuous (see Oakley and O'Hagan, 2004). The properties of this method are that (i) it will predict the model output at any of training data points with zero variance, (ii) that the predictions of the model output at other points will have non-zero variance, reflecting realistic uncertainty, and (iii) given sufficient training data it should be able to predict the model output to any desired level of accuracy. Therefore, GPR is a more suitable tool to model the non-linear relationship between AWC and ECa. In order to examine the accuracy of the fitted model in practice, we used the predicted residual sums of squares statistic which is a form of cross-validation and can be considered as a measure of predictive power. To compute this statistic after fitting the model of interest to the data, we remove each observation in turn from the whole data set and the model is refitted using the remaining observations. The out-of-sample predicted value is calculated for the omitted observation in each case, and the statistic is calculated as the sum of the squares of all the resulting prediction errors as follows:

$$PS = \sum_{i=1}^{n} (AWC_i - A\hat{W}C_i)^2$$

Where AWC_i is the ith observed AWC and $A\hat{W}C_i$ is the corresponding prediction obtained by using whole data set but for the ith data point. The calculated value of this statistic for the GPR model fitted to the data was 14.42, whilst the value for this statistic for the linear model fitted to the data was 541 which is approximately an order of magnitude larger than that of the GPR mode. A Gaussian Process Emulator (Oakley and O'Hagan, 2004), which is a non-linear model, was then used to deduce AWC from the EMI survey data. This data on the spatial variation in AWC can then be used to inform PI strategies for irrigation scheduling.

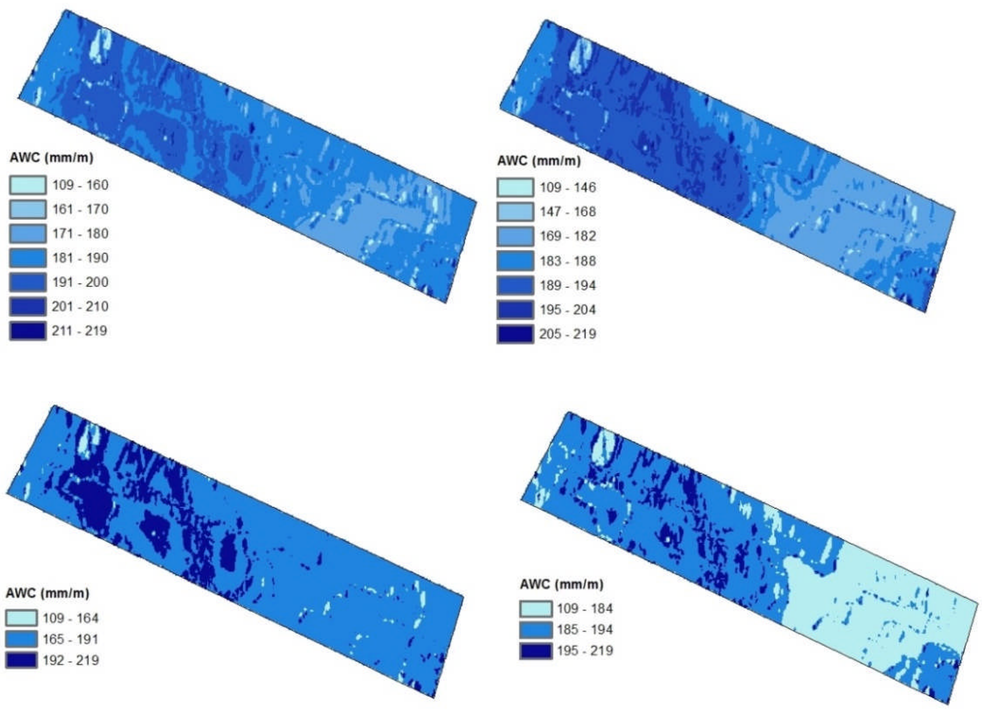
Various detailed studies on mapping spatial soil variability with EMI are found in the literature (e.g. James *et al*., 2003; Waine *et al*., 2000 and Hedley *et al*., 2009). The aim of this work was therefore not to accurately map AWC variability for the study site but rather to highlight the complexity and challenges in mapping spatial soil variability using non-invasive techniques such as the EMI. It would be impracticable and uneconomic in a humid environment to apply fully spatially variable water across a field to match such a fine resolution in spatial AWC variability. A more practical alternative for overhead irrigation is to define management zones which reflect relatively homogenous AWC areas. The critical factor here was to define an appropriate scale and resolution for these irrigation management zones (IMZ) that would be compatible with existing overhead irrigation application technology and current approaches to scheduling. This means that scheduled amounts of water can be applied by the system without introducing further hydraulic or engineering constraints.

7.2.3 Using geo-statistical methods to optimise irrigation management zones (IMZ)

The method of classification used and the range in AWC values determines the number, size and spatial distribution of IMZ. Various techniques have previously been developed to delineate these, with most based on observed differences in soil (Oliveira *et al*., 2003). Figure 54 shows, for example, how the classification method and number of derived classes can strongly influence IMZ delineation.

Figure 54 *Maps showing spatial variation in AWC generated from the EMI data, classified into 7 and 3 classes using equal interval (a) and Jenks natural break (b) methods.*

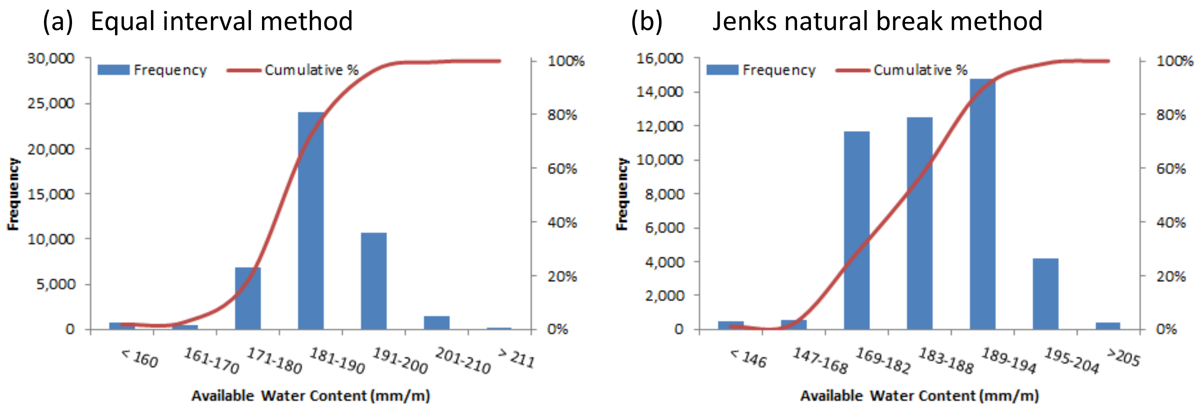
(a) Equal interval method (b) Jenks natural break method



For our field site, the AWC data were classified into 7 and then 3 classes, using two contrasting approaches, the equal interval method and natural (Jenks') break method (Figure 4). The Jenks' natural break classification determines the best arrangement of values into classes by iteratively comparing sums of the squared difference between observed values within each class and the class means. The "best" classification identifies breaks in the ordered distribution of values that minimizes the 'within-class' sum of squared differences. The natural break classification method therefore aims to minimize the variance within the group and maximize the difference between classes which is useful when considering AWC variability across an IMZ.

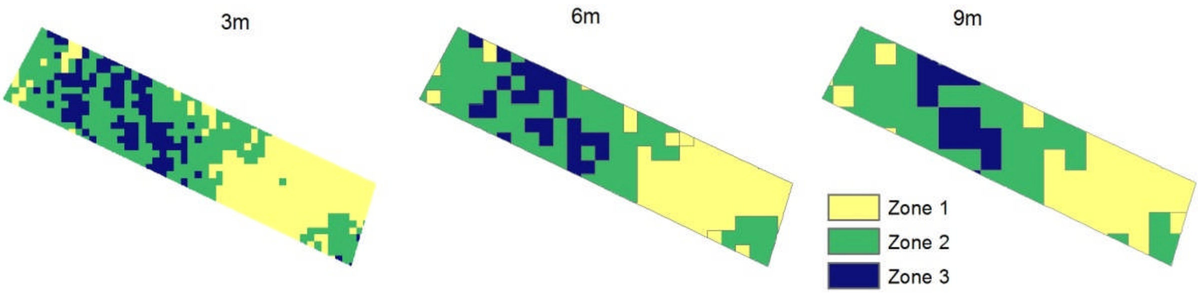
With equal breaks, over three quarters (80%) of the field is classified as one AWC class (180 to 190 mm/m) (Figure 55). In contrast, the Jenks' natural break classification identifies three AWC classes (ranging between 169 and 194 mm/m) each with a similar frequency (Figure 4). When the number of AWC classes is reduced from 7 to 3, three IMZ covering 55%, 33% and 10% of the field exist. However, when the equal breaks method is used two IMZ's covering 97% of the field result, which mask much of the variability in AWC (Figure 55). In reality, for this field, the range in AWC is actually relatively small, probably reflecting a deliberate decision by the farmer to grow high-value lettuce in a field with limited soil heterogeneity so as to minimise impacts on crop development, yield and quality. However, even with a small range in AWC, the spatial aggregation of IMZs is important, as their shape and area need to be compatible with the method of irrigation.

Figure 55 *Frequency and cumulative percentage of AWC values within each interval using a) equal interval and b) natural break classification.*



On the assumption that soil and crop water needs are similar across a field, a non-uniform water application will result in over and under–irrigation in the same plot with negative consequences on yield, quality, water and nutrient use efficiency. For that reason, overhead irrigation systems are designed to provide adequate overlapping from sprinklers to deliver the highest uniformity of water application. Any change in operation for a single sprinkler directly impacts on the wetted area and hence the depth of water applied under adjacent sprinklers. With hose-reel boom irrigators, applying variable irrigation at the sub-metre level is technically unfeasible given the short distance between individual sprinklers (2.5 to 4 m) and the need for overlap to achieve high uniformity. Hence, the raw AWC data must be aggregated into larger contiguous zones. These need to be large enough to be managed separately, yet small enough to minimize the soil AWC variability within them. To evaluate this issue, the AWC data were clustered using 3m^2, 6m^2 and 9m^2 pixel aggregations and classified into three IMZs using the Jenks' natural break method. The purpose was to analyse the impact of different management scales for delineating IMZs on field and water application variability. The range in AWC variation within each IMZ regardless of cluster scale is very similar in each IMZ. This is because extreme values are distributed across the field and within each IMZ. By taking the lower and upper quartiles, the differences become much more apparent across the three different zones. For example, at the 3m^2 scale, IMZ zone 1 appears to have the highest degree of variability. This is due to the large variability within a small area, which disappears when 6m^2 and 9 m^2 scales are used. The difference between 6m^2 and 9m^2 scale appears negligible (Figure 56).

Figure 56 *Irrigation management zones (IMZ) clustered at 3 m^2, 6 m^2 and 9m^2.*



7.2.4 Developing VRI on a mobile hose-reel boom

Most UK vegetable growers use hose-reel irrigation systems fitted with booms. The reel is parked at one end of the field, the boom pulled out with a tractor, and then the boom slowly pulled back in as the hose reel rotates and reels up the hose. The hose-reel system gives great flexibility to follow crop rotations and to fit to different field sizes across the farm. The booms are fitted with multiple overlapping sprinklers which provide better uniformity than a rain gun and allow the irrigation of strips that can match planting schedules. The choice of sprinklers or nozzles is determined mainly by considerations of drop size, to avoid crop damage whilst minimizing wind drift, and throw, to give adequate overlap and to spread the water to avoid runoff. The whole system is sized to allow sequential irrigation of adjacent strips around the field, returning to the first strip by the end of the scheduled irrigation interval.

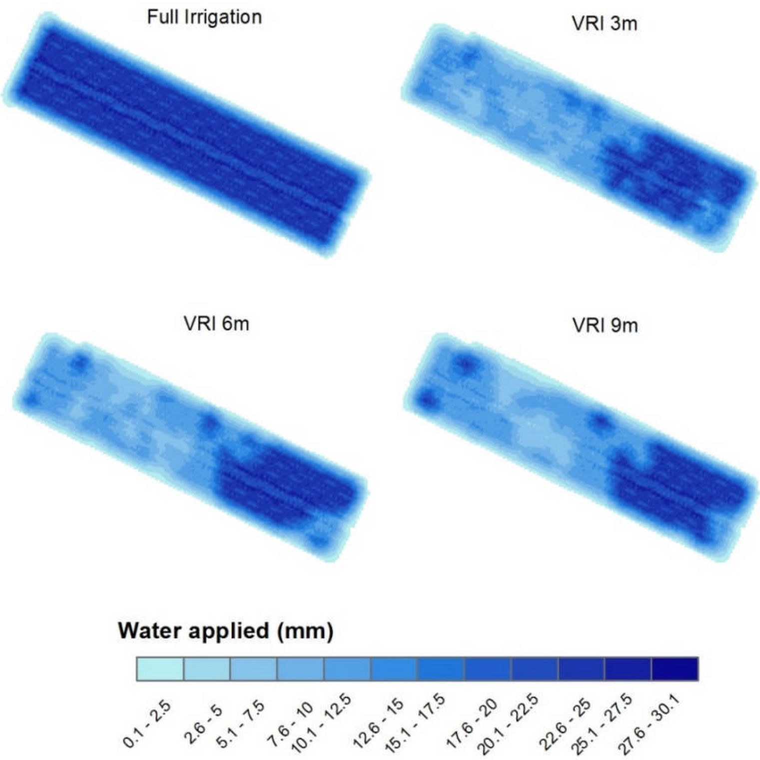
VRI can be achieved by fitting each sprinkler or nozzle with a remotely controlled on-off automatic valve. Fortunately this technology is already well developed for the golf industry, where individual sprinklers are operated sequentially along fairways and around greens. The relative duration of the on-off cycles will determine the depth of water applied. On-off control is preferred to trying to vary the pressure and flow rate, since that would also change drop sizes and throw and hence overlap. However, this setup still imposes various limitations on PI possibilities. The sequential irrigation of strips around the field requires that irrigation can only occur on the dates determined by the schedule for the lightest (lowest moisture retentive) soils. The throw of each sprinkler limits the minimum scale at which VRI can be physically applied. The overlap between sprinklers, which normally improves uniformity, makes it impossible to generate sharp changes in depth applied at boundaries between irrigation management zones or to stop irrigation across paths or for gaps in the crop. Some improvement can be achieved by using more sprinklers with smaller throws, but this raises the instantaneous application rate near to the boom leading to the risk of ponding and runoff, particularly on sloping fields.

A further issue is caused by the drive mechanism on the hose reels. Most UK systems use through-flow turbines to drive the reel, taking some of the energy from the water before it travels along the hose to the boom. However, this imposes a minimum flow rate before the turbine stalls and the pull-in ceases. Typically no more than half the nozzles could be closed simultaneously. Furthermore, a change in flow will typically alter the pull-in speed. The reel therefore needs to be fitted with a sophisticated speed controller, or the change taken into consideration by the control system. Using a piston drive, which bleeds off a portion of the water and then discharges it, would waste water, while a switch to separate motor-driven reel operation, as used in some other countries (e.g. Canada) would add costs. In this study, a commercially available boom (Briggs) was adapted by the addition of wirelessly controlled on-off solenoid valves. This consists of a four wheeled steel chassis fitted with 13 sprinklers (Nelson R2000WF) each 2.5 m apart and fixed 1.5 m above the ground level. Each sprinkler can be controlled by an on-off solenoid valve, controlled centrally via wireless radio links.

7.2.5 Hose-reel boom simulation

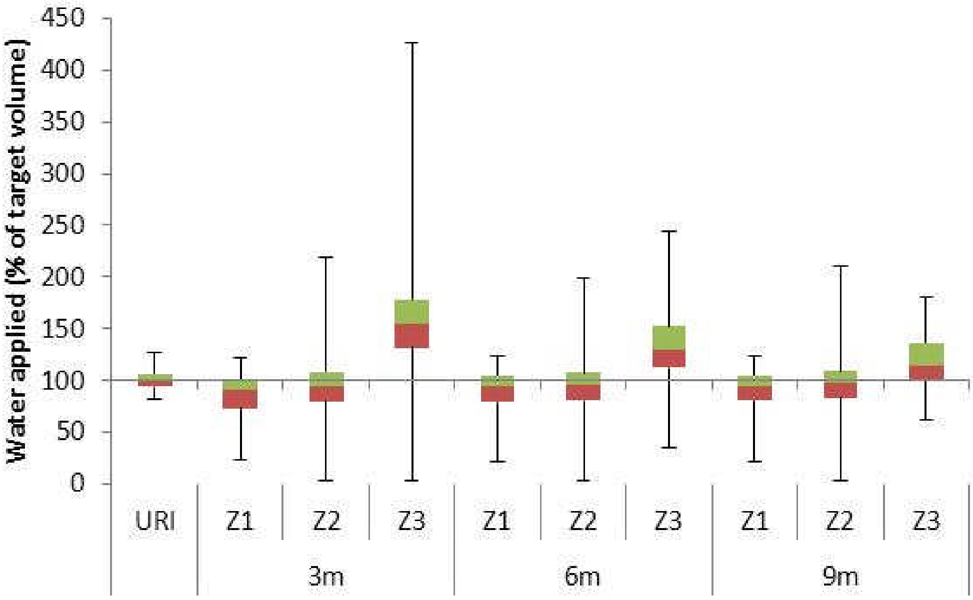
It was impractical to test all possible settings under full-scale field trials, particularly given the uncontrollable element of wind. A boom simulation model was therefore developed to aid optimization. This uses ballistic approach on a single drop to predict the wetting patterns under still or windy conditions (Carrion *et al*., 2000) and overlap wetting patterns based on the boom design and operational mode. The model is calibrated using the individual sprinkler water profiles (Nelson R3000) tested under 'no wind' conditions at different pressures (15, 25 and 35 m). Details on system design (including sprinkler spacing (2.75 m), the individual sprinkler height (1.35m), hose length (300m), pipe size (110mm), pulling speed (15m/h), boom width (33m) and land topography are all entered as inputs. These boom parameters were chosen to reflect typical operating boom settings used in field-scale horticultural cropping in the UK. Model outputs include the spatial distribution of water volume (depths) across the field when operating under either a uniform rate irrigation (URI) or variable rate irrigation (VRI) schedule. In the example run presented here, the system was scheduled to apply 23 mm water over the entire field under URI. Under VRI, using the zones previously defined at 3m^2, 6m^2 and 9m^2 grid pixel resolutions, the boom was programmed to try and apply the full (100%) irrigation capacity on zone 1 (low AWC), 50% across zone 2 (medium AWC) and 25% in zone 3 (high AWC). The resulting water application patterns are shown Figure 57.

Figure 57 *Spatial distribution of water applied (mm) under full uniform irrigation (URI) and variable rate irrigation (VRI) at 3m^2, 6m^2 and 9m^2 clustering resolution.*



The URI plot shows the non-uniformity inherent in the sprinkler arrangement, even with no wind. The VRI plots show the differences in depths of water applied in each IMZ, as the boom tries to respond to different target depths. The depths applied in each zone are compared in Figure 58 using a box and whisker plot to show the median, quartile and extreme values. With the zones defined at a 3m^2 grid resolution, the boom struggles to match the target schedule, with too little applied on zone 1 and too much on zone 2. With the larger zones, at 6m^2 resolution, the applications are closer, though still slightly under irrigating zone 1 and over irrigating zones 2 and 3. The performance is very similar with the 9m^2 resolution zones. These results show the inevitable problems due to sprinkler overlapping at the edges of the IMZ, and the resulting poor uniformity within each zone, although they are clearly an improvement over applying the full application (URI) where it is not needed.

Figure 58 *Simulated depths of water applied (mm) in each IMZ under uniform (URI) and variable rate irrigation (VRI), with zones defined at 3m, 6m and 9m scales. Depths are expressed as % of target application in that zone (100%, 50% and 25% for Z1, Z2 and Z3, respectively). Boxes represent the median, upper and lower quartile depths while error bars show the minimum and maximum range.*



These simulated depths could then be used as input into a biophysical crop growth model to assess the effects of different URI and VRI strategies on crop yield and drainage, and hence estimate any yield benefits (or penalty) and water savings. The model output data could also be used to assess the economic viability of precision irrigation by comparing the water and energy costs against conventional irrigation, under varying management and equipment management scenarios. These two aspects are covered in subsequent sections.

7.2.6 Are the potential benefits of PI significant in a humid climate?

The potential benefits from PI in a humid climate in England appear modest. For potatoes, the estimated water savings are around 20 mm/year on those parts of the field that would be over-irrigated by uniform irrigation (Table 20). PI has little impact on drainage during the growing season, which is mostly caused by unpredictable rainfall. In part, these results reflect the need to keep the SMD small during the scab-control period, irrespective of soil type. This is not necessarily the case for other high- value crops where scab control scheduling is not needed (for example, a shallow rooting salad crop). Further investigations on the potential benefits of PI are therefore needed to cover a broader range of crop types as these might show different responses. The simulation also assumed that evapotranspiration (ET) under irrigated conditions is the same irrespective of soil texture. In reality difference in soil texture may lead to differences in rooting depth or fertility such that plant growth and ET also differ.

7.2.7 At what scale does variable rate application need to be developed?

This study highlighted some challenges in mapping spatial variability in AWC from EMI data and delineating IMZ that are compatible with the spatial scale inherent in the overhead application systems used on vegetable crops in the UK. Many issues identified here are common to more arid climates. In particular, IMZs need to be large enough to be managed as discrete units, yet small enough to minimise soil AWC variability within them. The risk in defining zones that are too small to cope with overlapping sprinklers, resulting in high variation in the scheduled application depth, and 'edge effects' of many small units located within a larger homogenous IMZ have also been demonstrated. Rather than varying the application rate in each IMZ, Smith *et al* (2010) suggest an alternative would be to modify the irrigation interval or timing. In the UK farmers generally consider the crop risks associated with under-irrigation to be much higher than over-irrigation. At present, the relatively low marginal cost of water applied would be sufficient to discourage growers to save water via PI; other indirect benefits such as reduced variability in crop quality and reduced environmental impact would more likely convince growers of the benefits of PI in a humid climate. Finally, irrigation schedules are constrained by the operating characteristics of hose-reel boom system, with the whole run being irrigated on a specific day. This can limit the benefits from PI, since schedules cannot be optimised for each IMZ without further development to incorporate feedback from in-situ soil moisture monitoring. The number and location of soil moisture sensors needed to monitor the temporal variation in soil moisture content, and hence determine PI schedules, would also depend on the number of the IMZ needed for each field.

7.2.8 Can mobile hose-reel boom systems apply variable rate irrigation (VRI)?

The current booms used in field-scale agriculture could be re-engineered for variable irrigation rate by using a programmable controller and wireless on-off solenoid valves to regulate the operational mode of each sprinkler. However, the required variable application can only be achieved at a minimum scale set by the throw of the sprinklers, and the uniformity within each zone is lower than under URI. The hose reel requires a controller to maintain constant pull-in speed despite the variable flow, and the minimum flow is set by the drive turbine specification.

7.3 Assessing the agronomic (yield) impacts of precision irrigation

This section reports on a study combining experimental field data with biophysical crop modelling to assess the impacts of irrigation heterogeneity on onion yield. The AquaCrop model was calibrated and validated for brown onion (*cv Arthur)* and used to simulate yield variability under a set of contrasting soil and agroclimatic conditions assuming perfect (100% uniform) irrigation. The impacts of non-uniform irrigation as measured on-farm under two overhead systems (mobile hose reel fitted with boom and a linear move) were then evaluated using scenario analysis and multi-model runs. Stochastic modelling confirmed that the lowest yield (8.6 t DM/ha) occurs on the lowest moisture retentive soils under the driest agroclimatic conditions with non-uniform irrigation. There is much greater yield variability in dry years compared to wet years. In wet years, rainfall reduces the scheduled number of irrigation events and buffers the effects of irrigation non-uniformity on yield. Yields were more variable under the mobile hose reel system fitted with the boom compared to the fixed linear move system. The modelled yield variability under non-uniform was similar to the observed yields reported by growers based on an industry survey. The study highlights the importance of achieving high irrigation uniformity in dry years on light soils to maximise yield and provides useful data for evaluating the potential yield benefits that might accrue from precision irrigation.

Readers interested in the full description are referred to Perez-Ortola, M., Daccache, A., Hess, T.M., and Knox, J.W (2014) Simulating impacts of irrigation heterogeneity on onion (Allium cepa L.) yield in a humid climate *Irrigation Science* Doi: 10.1007/s00271-014-0444-2.

7.3.1 Context

A recent farmer survey showed that in the UK onions are typically grown on a range of soils, but sands to light sandy loams are preferred (Perez-Ortola 2014). Brown onions represent approximately 75% of the total cultivated area, with the most common drilled varieties including Centro, Arthur, Vision, Armstrong, Bennito, Hybelle, Hybing and Hytech. Sturon and Jagro are also widely grown from sets. Onion cultivation is concentrated in a relatively small number of regions (notably in eastern and central England) where light soils and warmer agroclimate conditions favour production.

In temperate and humid climates where irrigation is supplemental to rainfall, PI is less developed but nevertheless offers scope to make more effective use of rainfall, reduce the non-beneficial losses associated with irrigation (deep drainage, nitrate leaching) and provide farmers with evidence to demonstrate environmentally sustainable practices (Daccache *et al*. 2014). At present, most UK onion growers rely on overhead irrigation systems which are inherently non-uniform. However, despite interest in PI, no studies have assessed the impact of irrigation non-uniformity on onion yield, and hence the scope for using advanced irrigation technologies to reduce the impacts of irrigation heterogeneity. The aim of this part of the project was to therefore assess the impacts of irrigation on onion yield in the UK, by combining experimental and field data with biophysical crop modelling.

7.3.2 Modelling onion crop growth

The FAO AquaCrop model (Raes *et al*. 2009) was chosen as it can simulate the response of biomass, canopy cover and yield to daily variations in weather and irrigation. The model simulates soil water fluxes and then correlates soil water availability with crop stress. Using field data from a series of experimental trials, the AquaCrop model was first parameterised, then calibrated and validated using independent data. The model's ability to match simulated to observed yield was then statistically tested. Finally, a set of equipment and management scenarios were defined to assess the impacts of irrigation variability on crop yield. These scenarios comprised five contrasting agroclimatic seasons (weather years) and two soil types, to reflect the typical range of production conditions experienced by UK growers. The approach involved simulating 'perfect' (i.e. 100% uniform) irrigation, termed 'uniform'. The simulation was then repeated using a series of statistically defined on-farm irrigation events which reflected the observed heterogeneity, principally due to wind and pressure; this was termed 'non-uniform'. The 'non-uniform' irrigation events were based on catch-can measurements of uniformity conducted on a local farm under two different systems used on onions in Europe, (i) a mobile hose reel fitted with a boom and (ii) a large fixed linear move system.

7.3.2.1 Model calibration and validation

Between 2010 and 2012, a set of replicated irrigation trials on onion (cv *Arthur*) were conducted in a polytunnel environment at Broom's Barn Research Centre (Latitude 52.61°N; Long 0.56°E; 75 m asl), Suffolk, UK. A detailed description of the trials is given in Lacey and Ober (2011). A brief description of the datasets used for model parameterisation, calibration and validation together with information relating to measurement of canopy cover (CC), biomass, final yield and soil moisture content (SMC) are included here for convenience. The experiments were conducted on a loamy sand soil. Onions were drilled at a targeted planting density of 52 plants per m^2 between 18th and 21st March and harvested between 13th and 24th September in 2010, 2011 and 2012, respectively. The polytunnel shelter was installed between late April and early May each year to exclude rainfall and thus control the effects of irrigation on plant response. After polytunnel erection, irrigation was the only water input into the experiments. The trials were designed to evaluate the impact of different irrigation scheduling regimes on crop yield, quality and storability, in order to establish best practice guidelines for UK onion growers. Initially, eight treatments were defined (Lacey and Ober, 2011) which were modified after the first year to reflect more closely UK typical practices.

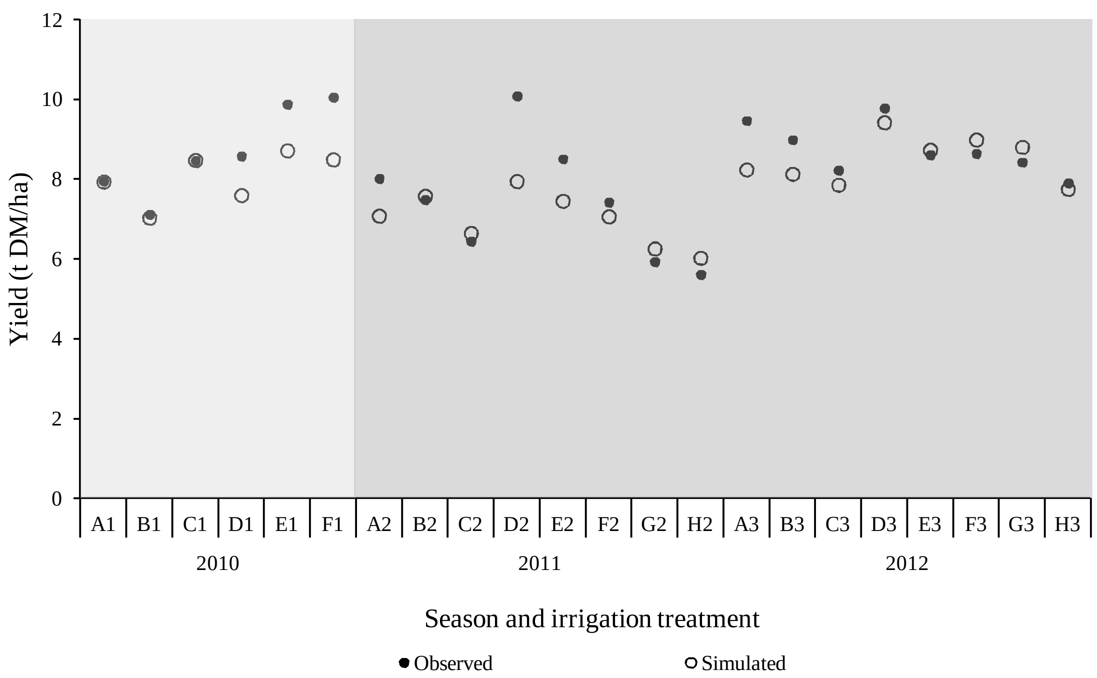
Daily weather (maximum and minimum temperature, relative humidity, radiation, and wind speed) were recorded under the polytunnel using an automatic weather station. Daily temperature and reference evapotranspiration (ETo) were also recorded from a nearby automatic weather station on the same site. Under the tunnels, solar radiation and wind-speed were found to be lower than outside, but temperature was very similar. Consequently, reference evapotranspiration (ETo) was 7 to 8% lower than outside in 2010 and 2011 and 3% in 2012 (Lacey and Ober 2011; 2012; 2013) especially between June and August.

Laboratory analyses were used to assess soil texture (Lacey and Ober 2011). Water content at field capacity (FC) and saturation (SAT) were established in the field following Zekri and Parsons (1999). Permanent wilting point (PWP) and total available water (TAW) were estimated from soil texture. Changes in soil moisture content (SMC) were measured using a capacitance probe (Decagon 10HS sensor) at depths of 0.1 m, 0.2 m and 0.3 m and logged on a 15 min time-step in each treatment plot. The irrigation schedule was based on the calculation of water depletion from soil moisture readings. Irrigation was applied using 8 sprinklers per treatment; individual irrigation events were triggered according to the measured available water content (AWC) within the rooting zone.

Canopy cover (CC), biomass, final yield and soil moisture content data were also collected by Lacey and Ober (2010, 2011) and used in this study to calibrate and validate the AquaCrop model. Canopy cover was estimated weekly using light interception records based on a hand-held spectral radiometer (Skye Spectrosense 2). Rooting depths were estimated from the in-situ capacitance probes based on data for depths of 0.1 m, 0.2 m and 0.3 m. Biomass (plant fresh weight) including above (green tops) and below ground (bulb) matter was measured through the growing season (at approximately 4 weekly intervals). At harvest, three randomly placed replicate samples (2 m^2) were hand harvested (with above ground tops removed), counted for population data, netted and weighted to assess green bulb yield.

The AquaCrop model was parameterized using a combination of the experimental field data collected by Lacey and Ober (2010, 2011) together with data for onions (*cv Arthur*) (e.g. base temperature, crop coefficient and seasonal variation, root characteristics, harvest index) published in the science literature. The model was calibrated using a trial and error approach on six of the eight irrigation treatments conducted in 2010. The model was validated against independent data from eight of the irrigation treatments from 2011 and 2012. Two irrigation treatments (extreme water deficits in 2010, G1 and H1) were not considered because they did not represent typical onion crop production. Figure 59 shows the simulated and observed onion yields for the model (2010) and validation (2011, 2012) periods.

Figure 59 *AquaCrop model simulated and observed brown onion (cv. Arthur) yield (t DM per ha) for selected irrigation treatments (Lacey and Ober, 2010; 2012) for the calibration (2010) and validation (2011-12) periods. Error bars show the maximum and minimum observations.*



7.3.2.2 Model performance

Aquacrop model goodness of fit was assessed using the Root Mean Squared Error (RMSE), Relative RMSE (RRMSE), and Model Efficiency (ME) based on the paired observed and simulated yield data (Loague and Green 1991). These statistical indicators are represented by:

$$RMSE= \sqrt{(1/n*\sum^{n}_{i=n} (S_i-O_i)^2)} \quad [1]$$

$$RRMSE= 100/M*\sqrt{(1/n*\sum^{n}_{i=n} (S_i-O_i)^2)} \quad [2]$$

$$ME= (\sum^{n}_{i=n}(O_i-M)^2-\sum^{n}_{i=n}(S_i-O_i)^2)/(\sum^{n}_{i=n}(O_i-M)^2) \quad [3]$$

Where:

S_i is the simulated and O_i the observed value, and M the average of the observed values.

The standard deviation (SD) was also calculated. The model fit was considered to be excellent if the RRMSE was less than 10%, good if it was between 10% and 20%, fair if it was greater than 20% and less than 30%, and poor if the values were greater than 30% (Jamieson 1991). The ME generates values that range from negative to 1. The closer the value is to 1, the greater is the robustness of the model (Loague and Green 1991).

7.3.3 Irrigation uniformity

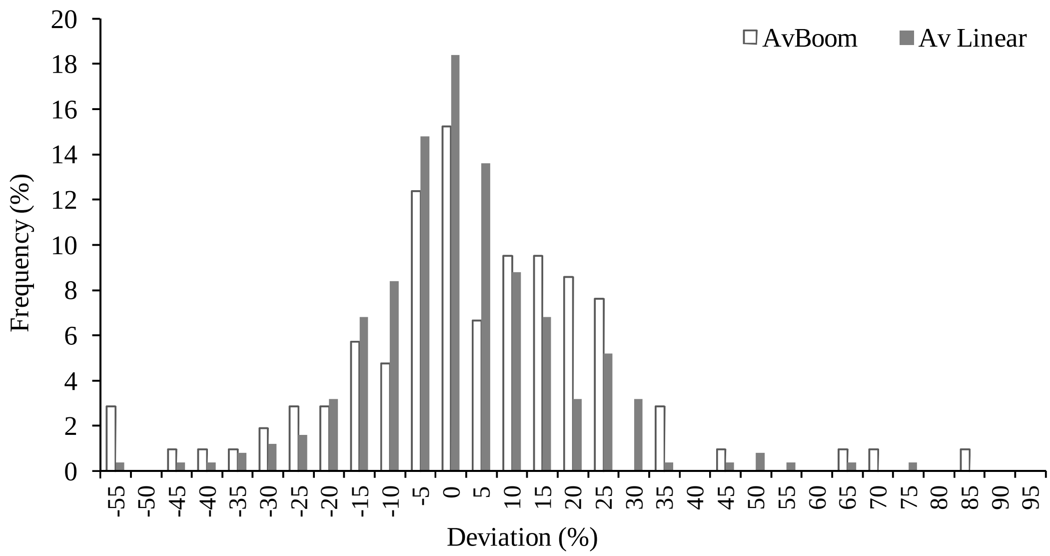
A series of on-farm assessments of irrigation uniformity were carried out between 2010 and 2013 using catch-can tests following the ASAE standard for overhead systems (ASAE 2003) at Elveden, Suffolk, close to Brooms Barn Research Station. The performance of two linear moves (350 m and 200 m span widths) was evaluated in August 2012 (two tests) and July 2013 (one test). In 2010, on the same farm, the uniformity of a hose reel fitted with a 60 m boom was evaluated on three separate occasions during the growing season. All tests were conducted on irrigation systems operating in flat fields growing onions. For each test, white (20 cm high and 21.5 cm diameter) catch cans with a sharp edge were placed every 1.83 m (equating to the distance between each onion bed) on the ground to form a transect perpendicular to the direction of irrigation system travel. System conditions including operating pressure, advance speed of the equipment, and the scheduled application rate were recorded. A portable weather station fitted with an anemometer was used to measure wind speed and direction during each field assessment, with data recorded on a 10 minute interval. After the irrigation system had moved over the transect, the volume of water in each catch can was measured. The Christiansen Coefficient of Uniformity (CU) (ASAE 2003) was calculated. Average CU values for the boom and linear move were 83% and 88%, respectively. In addition, the relative differences between the individual measurements and the average depths of water applied (Dev) were calculated from:

$$Dev (\%) = (x_i-X)/X *100$$

Where x_i is the individual records, and X the average value of that irrigation evaluation which coincided with the scheduled depth.

The individual catch-can measurements were plotted as a histogram (Figure 60). For the linear move, nearly half (50%) the observations deviated from the design (scheduled) application by between -5% and +5%; for the boom the equivalent deviation was a third (33%). Further analysis showed that the coefficient of variations (CV) for the linear move and boom were 17% and 23%, respectively.

Figure 60 *Histogram showing results the average variability in irrigation deviation (%) under a hose reel fitted with a boom and a linear move irrigation system.*



7.3.4 Scenario modelling

The impact of irrigation non-uniformity on onion growth and yield will vary depending on the weather conditions during the growing season, soil type and water holding characteristics, and type of irrigation system. Selected outputs from the industry survey of farmer practices (Perez-Ortola 2014) were used to identify the most important regions where onions were grown, the local soil and agroclimatic conditions, typical irrigation practices (methods of application and schedules) and range of planting dates and harvesting periods. In order to evaluate the relative importance of each of these factors, and their interactions on final onion yield, a set of 20 scenarios were defined.

7.3.4.1 Agronomic conditions

Two soils, a sand and light sandy loam, were chosen and their textural and water holding characteristics defined. For all scenarios, a fixed planting date (1st March) and a planting density of 50 plants per m^2 were assumed to match farmer practice. For each soil type, an irrigation schedule as recommended by commercial agronomists providing scheduling advice to farmers was used; this was defined to maximise both yield and quality, assuming that the crop cycle is split into two stages (i) canopy development, and (ii) after bulbing. Irrespective of soil type, irrigation was stopped two weeks prior to harvest to allow the mature crop to dry, a practice commonly adopted by commercial growers, and to avoid structural soil damage from harvesting machinery.

7.3.4.2 Weather conditions

In order to reflect the range of agoclimatic conditions under which UK onion production occurs, a set of contrasting weather years were selected. Previous studies have used a variable termed maximum potential soil moisture deficit ($PSMD_{max}$) to assess the impact of weather on irrigation demand (e.g. Rodríguez Díaz *et al*. 2007; Knox *et al*. 2010b). The PSMD reflects the cumulative balance between rainfall and ETo and has the advantage over other aridity indices in that the distribution of rainfall and ET throughout the year is taken into account, which is important in regions where summer rainfall can be significant. Using historical (1961-2011) daily time-step data for rainfall and ETo, the $PSMD_{max}$ in each year was calculated for five weather stations selected to be representative of the main onion production areas in England. The only pre-requisite for the Aquacrop modelling was that each selected year had a minimum growing degree day (GDD) from March to September of 1425°C (equating to the seasonal onion requirement to complete a crop cycle).

$PSMD_i = PSMD_{(i-1)} + ETo_i - R_i$ [1]

Where: $PSMD_i$ is the PSMD on day *i*, and ETo_i and R_i are reference evapotranspiration and rainfall on day *i*. Five individual station-years were then selected to correspond to years with the lowest and highest $PSMD_{max}$ and those with 20%, 50% and 80% probabilities of exceedance (Table 21). These contrasting climate years are referred to as 'very wet', 'average wet', 'average', 'average dry' and 'very dry', respectively.

Table 21 *Summary of selected weather stations and data used for defining each climate year.*

Weather station	Location (latitude, longitude)	$PSMD_{max}$ (mm)	Climate year	Year
Buxton (Norfolk)	52.75°; 1.30°	62	Very wet	1968
Brooms Barn (Suffolk)	52.26°; 0.56°	105	Average wet	2002
Silsoe (Beds)	52.00°; 0.42°	255	Average	2004
Cambridge (Cambs)	52.20°; 0.12°	340	Average dry	1984
Silsoe (Beds)	52.00°; 0.42°	562	Very dry	1976

7.3.4.3 Simulating 'uniform' and 'non-uniform' irrigation

Two overhead application methods, a mobile hose reel fitted with a boom and a linear move irrigation system, were included in the study, as described previously. The AquaCrop model was used to estimate irrigation need and yield for brown onion (*cv Arthur)* for the two soil types and five weather years assuming 'uniform' irrigation. This represented the reference or 'baseline' condition. Probability distributions from the on-farm irrigation evaluation were then used to generate 100 individual datasets for each of the five weather years, to represent 'typical' imperfect (i.e. non-uniform) irrigation. Each dataset contained information on the likely variation in depth of water applied (mm) for each scheduled irrigation event. A script was written using the statistical environment R (http://www.r-project.org/) to produce AquaCrop input files by combining the reference irrigation schedule with the random variations derived from the probability distribution. Two thousand input irrigation files were generated; comprising 100 statistically derived irrigation distributions, for two irrigation systems (boom and linear move) and five statistically defined weather years (i.e. very wet, average wet, average, average dry, and dry) on two soils (sand, sandy loam). The AquaCrop model was then re-run using the 'non-uniform' irrigation datasets. Yield differences between 'uniform' and 'non-uniform', by soil type and weather year, were derived. For all simulations, the simulated soil conditions in Aquacrop were assumed to be at field capacity on 1st January each year, and for each soil, topsoil characteristics were assumed uniform through depth.

7.3.5 Results and discussion

7.3.5.1 Model parameterisation

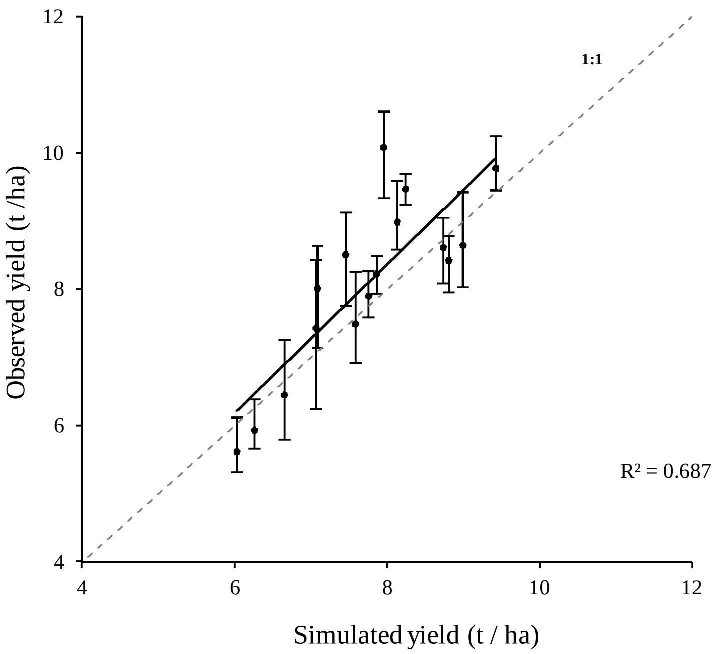
The simulated data for soil moisture content and canopy cover correlated well to the observed values for both the calibration and validation periods. Table 5 summarises the calculated values for the RMSE, RRMSE and ME as well as the standard deviation (SD) of the observed yield. The estimates are shown by year and for all years combined.

The RMSE varies between 0.64 and 1.06 t DM ha^{-1}, which corresponds with the range of standard deviation (0.62-1.43). The ME values range from -0.06 to +0.52. Overall, the model performance is therefore considered good, as shown by the RRMSE values of between 10 and 20% (Table 5) and shown in Figure 61.

Table 22 *RMSE (t/ha), RRMSE (%), ME and standard deviation (SD) for AquaCrop model simulated and observed onion yields, based on experimental data from 2010, 2011 and 2012.*

Year	RMSE (t/ha)	RRMSE (%)	ME	SD (t/ha)
2010	1.06	12.3	0.19	1.18
2011	1.03	13.7	0.52	1.43
2012	0.64	7.3	-0.06	0.62
Overall	0.92	11.1	0.48	1.28

Figure 61 *AquaCrop model simulated and observed onion yield (t/ha) for the validation period.*



The model matched observed yield values for those irrigation treatments where the irrigation was triggered at 50% AWC during the stage of canopy development. A slight mismatch (average deviation of -8%) between observed and simulated yield occurred when irrigation was applied more frequently at a lower soil water deficit. The model also showed very good correlation (R^2 0.93) in simulating water content in the root zone in response to irrigation and crop transpiration. The model's ability to simulate crop development (using crop cover as an indicator) was good. There are no other directly comparable results for onion, but other studies using the AquaCrop model have shown values for RRMSE of 22.6% and ME of 0.92 (Rinaldi et al. 2011), normalized RMSE (nRMSE) values of between 4 and 13% (Wellens et al. 2013) and an R^2 value of 0.66 and RMSE of 743 kg ha^{-1} for wheat (Mkhabel and Bullock 2012).

7.3.5.2 Uniform irrigation

The modelled irrigation needs and yield for a 'very wet', 'average wet', 'average', 'average dry', and 'very dry' year are shown in Table 6 for 'uniform' irrigation. Higher yields were modelled during the 'wetter' season: 10.5 and 10.2 t DM ha^{-1} on the sandy and sandy loam soils, respectively; compared to 9.6 t DM ha^{-1} for an 'average' season on both soils, and 8.9 and 8.7 t DM ha^{-1} under 'very dry' conditions. The simulated yield for the 'very wet' year was the highest; however, production could still be of very poor quality. Rainfall was the highest through the season (500 mm). Due to low temperatures, crop maturity (determined by accumulated GDD) was not reached until 11th October (Table 23). A yield of >10 t of DM ha^{-1} would correspond to a green yield of >70 t ha^{-1}. However, due to a very wet September (159 mm rainfall of 630 mm annually) there would be problems for the crop to reach maturity, whilst farm machinery would encounter major trafficability problems at harvest due to severely wet ground. Furthermore, quality issues would most likely develop due to the high moisture content, as wet bulbs can develop problems (mainly related to fungal diseases) during storage.

Table 23 *Simulated irrigation water requirement (mm) and yield (t DM ha^{-1}) for brown onions (cv. Arthur) for each climate year, by soil type, assuming perfect (100% uniform) irrigation.*

Climate year	**Seasonal irrigation need (mm)**		**Simulated yield (t DM ha^{-1})**		**Maturity date**
	Sand	Sandy loam	Sand	Sandy loam	
Very wet	90	105	10.5	10.2	11th Oct
Average wet	96	110	9.6	9.4	13th Sept
Average	164	150	9.6	9.6	12th Sept
Average dry	198	265	9.9	9.7	11th Oct
Very dry	286	360	8.9	8.7	19th Sept

Irrigation increased for average conditions from 96 and 110 mm to 198 and 265 mm from the 'average wet' to the 'average dry' seasons, for sandy and sandy loam soil types, respectively. During the 'very dry' year, seasonal (March to mid-September) rainfall (138.4 mm) and ETo (682.5 mm) resulted in an irrigation need of 286 mm and 360 mm for the sandy and sandy loam soils, respectively. This season could have been the most productive if the irrigation schedule had been able to match crop water requirements. However, the irrigation schedule led to some crop stress, with several peaks in stress affecting leaf expansion, inducing stomatal closure, as evident in the outputs from the model simulation, suggesting that the irrigation schedule for an average year might not be appropriate under extreme conditions of aridity.

7.3.5.3 Non uniform irrigation

The onion yield for the 2000 simulated seasons are summarised in Figure 62 as a box and whisker plot. Onion production values for each scenario and irrigation system did not correspond to a normal distribution, therefore, a Kruskal-Wallis (1952) test was undertaken to identify any significant differences between groups (Table 24). Figure 62 and the statistical analyses show that the simulated yield on sandy soils were always higher than on a sandy loam; average yield produced under the linear move irrigation application system was always greater than under a mobile boom system. Yield production related to the climate year showed a similar pattern to that for uniform irrigation. The highest yield and lowest variability (IQR) was obtained under the wettest climate conditions. The greatest variability and lowest yield 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 the sandy loam) compared to wetter conditions, thus exacerbating the effects of the irrigation non-uniformity. In wetter years, when irrigation is less frequent, rainfall compensates for the fewer irrigation applications. The yield variability predicted under the boom application system was greater than for a linear move system.

Table 24 *Summary Kruskal-Wallis (1952) analysis shows average yield for groups considering the interactions between three factors (soil, climate year and irrigation method) and their interquartile range (IQR). Letters indicate whether the groups are significantly different.*

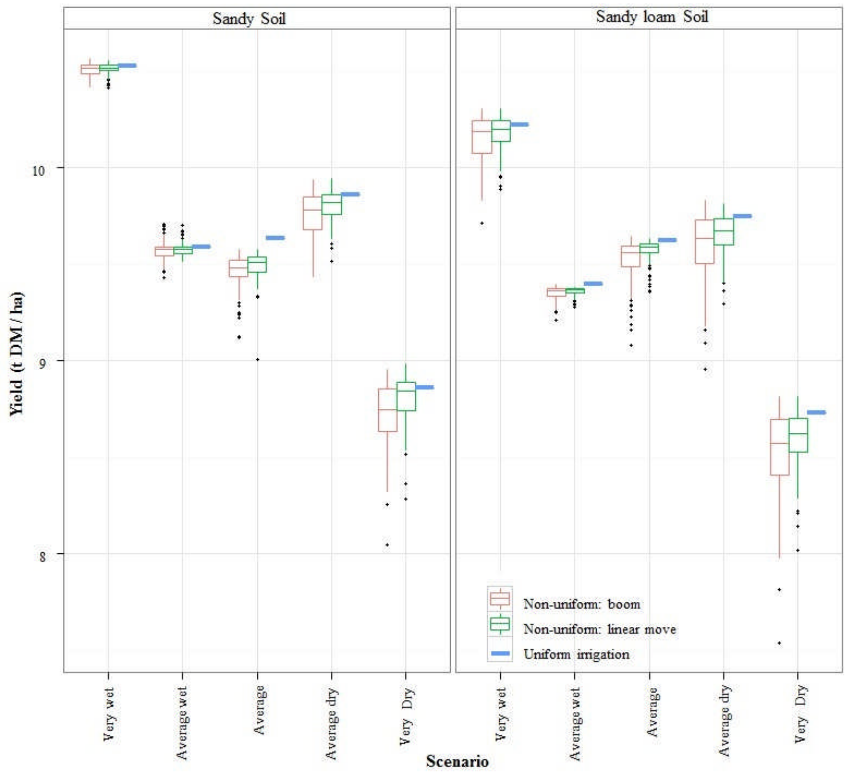
Significant group	Treatment / interaction (climate -method-soil)	Mean (t DM ha^{-1})	IQR (t DM ha^{-1})
a	Very wet-boom-sand	10.51	0.05
a	Very wet-linear-sand	10.51	0.03
b	Very wet -linear-sandy loam	10.18	0.11
b	Very wet-boom-sandy loam	10.15	0.17
c	Ave dry -linear-sand	9.81	0.10
d	Ave dry -boom-sand	9.75	0.17
e	Ave dry -linear-sandy loam	9.65	0.13
f	Ave .dry -boom-sandy loam	9.60	0.22
fg	Average-linear-sandy loam	9.58	0.04
fg	Ave. wet-linear-sand	9.58	0.03
g	Ave. wet-boom-sand	9.57	0.05
h	Average-boom-sandy loam	9.52	0.11
i	Average-linear-sand	9.49	0.08
j	Average-boom-sand	9.46	0.09
k	Ave. wet-linear-sandy loam	9.36	0.02
k	Ave. wet-boom-sandy loam	9.35	0.04
l	Very dry -linear-sand	8.80	0.15
m	Very dry -boom-sand	8.73	0.22
n	Very dry -linear-sandy loam	8.59	0.18
n	Very dry -boom-sandy loam	8.51	0.29

The factor (soil, irrigation and weather year) and their individual interaction (soil-year, and year-irrigation) were found to be significant as well as the triple interaction ($P < 0.05$). The interactions between soil and weather condition resulted in significant differences between all combinations. Table 24 presents the significance groups that result from the analysis of the triple (soil, weather and irrigation system) interactions and adds statistical evidence to the data shown in Figure 62. The highest yield was produced during the 'very wet' season on sandy soils, and the lowest during the 'very dry' season on a sandy loam soil. The study of the combined effects on yield production of irrigation non-uniformity produced by the two irrigation systems and the weather 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 between the three factors. The greatest variability in yield occurred under boom irrigation systems in 'very dry' conditions (IQR of 0.29 t DM ha^{-1}) on sandy loam, followed by the same conditions on a sandy soil (IQR of 0.22 t DM ha^{-1}), boom on sandy loam during and 'average dry' year (0.22 t DM ha^{-1}) and linear move on sandy loam during 'very dry' conditions (0.18 t DM ha^{-1}). The lowest variability occurred under hose reel fitted with boom for the wettest conditions (IQR<0.05 t DM ha^{-1}). These results show that during 'average dry' and 'average' weather 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 to under 'average' weather 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 between irrigation systems on sandy soils. Under ‘average wet’ and ‘very wet’ weather conditions, significant differences occur only between soils.

Figure 62 *Box and whisker plot showing Aquacrop model simulated onion yield (t DM ha^{-1}) under ‘uniform’ irrigation and ‘non-uniform’ irrigation, using a hose reel with boom and a linear move application system, on a sandy and sandy loam soil, for each climate year (very wet, average wet, average, average dry, and very dry).*



7.3.6 Yield implications due to irrigation heterogeneity

Onion yield under non-uniform irrigation is generally lower than under uniform application. Uniform applications produced average yields above the median (Q_2) and in some cases in the highest quartile. This suggests that between 50 and 75% of the results of non-uniform irrigation simulations are below the yield produced in the case of uniform applications. These differences are greater for the drier years and in the case of boom fitted to hose reel systems. The greatest differences between the yields produced under a uniform irrigation and under a non-uniform application are found during the ‘very dry’ and the ‘dry’ seasons, with greater differences on sandy loam soils and under boom irrigation systems. On a sandy loam soil the differences between the median and simulated yield under uniform irrigation were approximately 100 kg DM ha^{-1} for the driest seasons. Differences were slightly smaller on sandy soils.

This study highlights the potential improvement in yield that could be achieved via implementation of advanced irrigation technologies to reduce non-uniformity. This could either be through better irrigation management (for example, minimising the effects of wind by irrigating at night, reducing pressure variation during pump operation, or by reducing sprinkler spacing to increase overlapped areas and eliminate risks of ‘dry spots’. Large changes in topography (elevation) could also negatively impact on sprinkler performance, although modern pressure compensating controllers help to offset this problem.

Assuming no other constraints on productivity (for example, due to pests, disease or inadequate fertilisation) the yield produced under a perfectly uniform irrigation is the target growers could achieve by managing their irrigation systems optimally for a given schedule. The scenario modelling to assess non-uniform irrigation applications under identified the likely impacts that irrigation heterogeneity can have on yield. The modelling showed that under drier conditions, irrigation non-uniformity can generate yield variations of up to 10% and lower average yields. Yield reductions were also greater for a crop irrigated using the hose reel with boom system compared to the linear move due to better irrigation uniformity. These effects were greatest on sandy loam soils in the most arid years when the cumulative impact of non-uniform irrigation is greatest. Conversely, under wetter conditions, with fewer irrigation events, the impacts of irrigation heterogeneity on yield appear to be moderated by rainfall, thereby reducing the additive effects of non-uniformity.

In comparison to the modelled estimates, an industry survey of UK onion growers identified reported seasonal yield variability of between c30% (in-field) and 40% (field to field) (Perez-Ortola, 2014). The main factors accounting for these reductions were attributed to soil, irrigation, fertilization and other characteristics that vary within and between individual fields. The yield variability shown by the scenario modelling represents the variability likely to occur on a homogeneous soil solely due to non-uniform irrigation.

7.3.7 Summary

By combining three years' experimental field data with extensive farm irrigation and cropping records, the AquaCrop model has been successfully calibrated and validated for brown onion (*cv Arthur)* cultivation in the UK. Statistical analyses confirm significant relationships between observed and simulated canopy cover, soil moisture content through the growing season, and yield. The Aquacrop model has then been used to study the impacts of irrigation heterogeneity (non-uniformity), soil type, and method of irrigation on final crop yield, across a range of agroclimatically contrasting years. Irrigation system performance and the degree of heterogeneity were shown to have a major impact on onion yield and its variability. The results showed a reduction in yield and increase in yield variability, especially in drier years, attributed to non-uniform irrigation. However, the magnitude of impact depends on soil texture and irrigation system. In the UK, the summer rainfall varies markedly. In drier summers, UK onion production could be reduced by approximately 0.8 to 0.9 t green yield per ha (considering DM content of 11-13%) due to irrigation non-uniformity, highlighting the importance of maximising irrigation uniformity for a given application system. Identifying and quantifying other sources of yield variability in onion production is also needed in order to put the impacts of these irrigation heterogeneity impacts into context.

7.4 Assessing economic viability of precision irrigation

The benefits of precision irrigation (PI) will of course be site and crop specific and depend on a range of factors such as the magnitude of soil variability within the field, climate conditions, method of irrigation and cost of water (particularly if storage is required). The final part of the study therefore involved undertaking a financial impact appraisal to assess the economic viability (costs and benefits) of investment in precision irrigation technology and its sensitivity to key variables. The approaches developed and key findings are summarised below.

7.4.1 Context and approach

Precision Irrigation is an emerging practice using advanced irrigation management and application technology combined with sophisticated sensing technologies and modelling tools to achieve a spatial variation in the rate of irrigation, to match the spatial variation in crop water requirements. It aims to reduce yield variability, energy consumption and water use and increase yield, which should increase economic efficiency and reduce environmental impacts. The paper reports a cost-benefit analysis of precision irrigation and conventional irrigation compared to rainfed production, using a travelling hose-reel irrigator fitted with a boom, for onions grown on a site in the temperate climate of the East of England (UK). It also evaluates selected environmental outcomes (water saving and CO_2e emissions). Results showed that the precision irrigation system modelled generates higher environmental outcomes in terms of water saving (about 23% less water consumption) and added value of irrigation water (2.3 £m^{-3} versus. 1.8 £m^{-3}), and CO_2e emissions are approximately 20% lower. Nevertheless, ignoring any crop yield and quality differences, net financial returns are slightly lower (by about 5%) than for conventional irrigation, due to the increase control and sensor costs. Overall, although the precision irrigation leads to significant water savings and energy efficiency benefits, these alone do not cover the additional costs. However, crop yield or quality benefits, higher water costs (or values) and/or greater soil variability would make investment in precision irrigation more viable.

The potential benefits of managing crops using precision techniques include the obvious financial benefits from higher water efficiency and energy savings, the agronomic benefit of increasing the marketable yield and the positive environmental impacts (Ghinassi 2010; Bongiovanni and Lowenberg-Deboer 2004; Zhanga et al 2002). Nevertheless, the rate of adoption of these technologies has been slower than predicted (McBratney et al 2005). One constraint towards the implementation of precision technology in agriculture suggested is the high cost and availability of well-trained and knowledgeable people who have agronomic skills as well as computer and information management skills (Kitchen et al 2002). Another of the main constraints suggested is the limited number of economic and environmental assessments (Evans and King 2012; Smith et al 2010; Robertson et al 2007).

While available literature indicates that precision technologies can contribute in many ways to long-term environmental and economic sustainability of different agricultural practices e.g. seeding, weeding, pest control (Pedersen et al 2006; Bongiovanni and Lowenberg-Deboer 2004); the published research on the potential economic benefits of precision irrigation is lacking in quantity, and what is available shows conflicts in the results. This could be due to the diversity of factors affecting the systems, many of which have been discussed in previous studies (Evans and King 2012; Almas et al 2003), such as: the field variability and the optimal IMZ, climate variability, the crop value, and the economies of scale and the useful life of the equipment.

Most previous assessments to evaluate the viability of VRI have been carried out in arid or semi-arid regions with a focus on centre-pivot systems. Lu et al (2005) compared the economic feasibility of VRI on centre-pivot with uniform application and water application strategies each strategy covering a percentage of the irrigation water requirement in the South Carolina, USA. Even though VRI generated higher yield and reduced water costs, the benefits did not cover the extra-costs of the technology used for the VRI to be feasible. Almas et al (2003) assessed the investment costs in VRI on centre-pivots and evaluated the breakeven yields of different crops grown in Texas (USA) needed to offset the additional cost; they showed that VRI would be feasible for most crops grown in the region. This confirmed similar studies carried in Texas using yield mapping techniques concluding that higher yield variability within a field would justify the investment of VRI (Marek et al 2001). In Idaho (USA) a field experiment was conducted to assess the profitability of VRI on centre-pivot for potatoes; results showed a higher gross income compared to uniform application but noted that economic benefits should be higher for the economic viability of VRI technology under a 3-5 years rotation constraint (King et al 2006). In south-eastern USA, Nijbroek et al (2003) used crop modelling to determine optimal irrigation schedules for the VRI on centre-pivot for a 9.94 ha of soybean; positive returns were attained and the authors suggested that they could be higher for larger field size and increased soil variability within the field.

In respect of travelling sprinkler systems, Turker et al (2011) used crop modelling and soil mapping to assess the feasibility in terms of water saving and breakeven farm size for VRI on a travelling hose-reel irrigator fitted with a boom in two case studies in Black Sea area. The water saving potential of the VRI technology in this case was around 5% and the breakeven farm size was 350 ha.

However, only a few studies have been published on the viability of VRI in temperate climates. Hadley and Yule (2009) and Hadley et al (2011) modelled the water saving benefits of switching to VRI on linear move sprinkler and centre pivot systems in three different case studies in New Zealand with different cropping patterns. Despite the high savings in water, which varied between 19% and 26%, the authors did not estimate the economic benefits and the viability of the adoption of VRI.

Therefore, the major objective of this paper is to fill an apparent gap in the scientific literature regarding the economics and environmental benefits of precision irrigation (VRI) using a travelling hose-reel irrigator fitted with a boom in a temperate climate. Consequently, the research will involve the integration of various modelling techniques, an approach previously used in the literature to deal with variable application technology in precision agriculture (Ahmad et al 2012; Hedley et al 2011; Turker et al 2011). We will establish the costs and benefits of conventional and precision irrigation applied to onions (*allium cepa*) in the East of England (UK), and compare them to rainfed production, taking into account climate and soil variability. Selected financial and environmental indicators on the life cycle of the investment will be determined. Finally a sensitivity analysis will be conducted to see the effects of variation in production factors on the final outputs.

7.4.2 Methodology

The experimental field modelled is located in the Breckland district of Norfolk (UK), in the East of England. It was concurrently being studied by Perez Ortola (2013) as part of an associated project. It has a total area of 33.9 ha on free-draining sandy Breckland soil (Cranfield University, 2013). It presents relatively low soil heterogeneity; for this study we have notionally divided the field into three irrigation management zones based on the Normalised Difference Vegetation Index (NDVI) calculation. NDVI is a satellite vegetation indicator to quantify the fraction of photosynthetically active radiation absorbed by vegetation and therefore to establish the condition of the vegetation for a given pixel for a given time (Weier and Herring 2000; Gillies and Carlson 1995). The irrigation management zone of the field had the following characteristics: IMZ 1 sandy soil representing 70% of the field area, and IMZ 2 sandy loam soil and IMZ 3 loamy sand each representing 15% of the field area). IMZ zones need not necessarily each in one piece, but should be in sufficiently large blocks for the VRI equipment to irrigate each differently.

The whole field was cultivated with spring-sown onions (Arthur variety) on beds of 1.8 m in width, with each bed holding 4 rows of onions. The bulbs are drilled around mid-March and harvested by the end of September. Irrigation water is pumped from boreholes on the farm to storage reservoirs and thence to the field, subject to an abstraction license as required by the Environment Agency (EA), which manages water resources in England and Wales and sets water abstraction charges (EA, 2013). Irrigation is applied using a travelling hose-reel irrigator fitted with a boom 64 m wide structure with 22 sprinklers in total, including 2 end impact sprinklers (covering a 72 m irrigated width), distributing water at low pressure in precise drops directly above the crop. This type of hose-reel system is simple and easy to operate; they have low labour requirements, are built from long life components and require relatively low maintenance. Fitting booms with numerous small sprinklers gives the benefits of smaller droplets, reduced evaporation and less wind drift during irrigation compared to rainguns. The boom system has been adapted for VRI using individual remotely controlled solenoid valves on each sprinkler, a precision technology that has been abundantly described in the literature particularly for centre pivot and linear move systems (e.g. Chávez et al 2010a; Chávez et al 2010b).

7.4.2.1 Irrigation water requirements and yield

The daily weather data series used in this modelling were from Brooms Barn weather station in Suffolk (UK) over the 20 year period between 1992 and 2011 (52.2601 N; 0.56723 E). These data included daily rainfall, reference evapotranspiration (ET_0) and maximum/minimum temperature. The FAO crop model AquaCrop was used to calculate the irrigation water requirements and attainable yields of the onions, as a function of water consumption, for the selected historical weather data and the three soil types (Steduto et al 2009; Doorenbos and Kassam 1979). AquaCrop has been previously calibrated and validated for onion crops in the UK by Perez Ortola (2013). She suggested an irrigation schedule that raises the soil to field capacity whenever the soil moisture deficit reaches 50% of the readily available water (RAW) before "bulbing" and 60% after "bulbing".

7.4.2.2 Financial investment appraisal

A Financial Investment Appraisal (FIA) was carried out to look into the different costs and benefits under conventional irrigation (CI) and precision irrigation (PI), compared to rainfed production, and the profits of each investment from the point of view of a private individual or organisation. The production costs outside irrigation are almost identical for rainfed, CI and PI irrigated onion production, and hence not included in this assessment.

Irrigation costs include the initial capital costs, the variable costs of irrigation and the annual charges for water abstraction. Among other factors, these vary with the irrigation water requirements and the type of application system (e.g. Morris et al 1997; Morris 1994), as well as location. The capital cost of the irrigation systems and precision technology was calculated here based on updated market figures from a UK equipment supplier, "Briggs Irrigation UK", excluding VAT and was discounted for its useful life ($n = 10\ years$) at the rate recommended for the UK public sector for projects of between 0 and 30 years ($i = 3.5\%$) assuming no inflation would occur during the useful life (HM Treasury 2011). The fixed (mostly capital) cost includes also the insurance and maintenance, estimated at 1% per annum each.

The additional capital costs for using precision technology relate to the initial mapping of soil properties (using an EMI scanner in this case), the control systems for the sprinklers and the additional soil moisture probes. The number of sensors required in turn relates to the heterogeneity of the soil in the field.

Variable costs of irrigation relate to the water charge, the social cost of carbon and the costs generated from the irrigation activity e.g. labour costs, tractor usage and the diesel consumption for pumping and for tractor usage. The latters were calculated updating the figures of Ahodo (2012).

The annual water abstraction charge (AC) in England is currently (2013/14) the sum of the standard charge (calculated under a two part tariff) plus an environmental compensation charge added by the regulator for the recovery of compensation costs associated with the revocation or variation of abstraction licences. Under the two part tariff, half the standard charge is based on the authorised maximum annual quantity specified in the license (V_M), modelled here as the average water requirement in a dry year under each system. The other half is based on the volume actually abstracted (V_A). The compensation charge is based on the maximum licensed quantity. Unit rates for groundwater abstraction in the Anglian Region in 2013/14 were applied (EA 2013).

The social cost of carbon is an estimate of the economic damage to the climate associated with the increase in CO_2 emissions. An expanding branch of science has estimated the potential costs of climate change expressed as the "Social Cost of Carbon" (SCC), defined as the damages caused by each additional ton of carbon dioxide (CO_2) released into the atmosphere (Ackerman and Stanton 2010), and accounting for the other greenhouse gases by using the "carbon dioxide equivalents". To include this cost into the variable costs of conventional and precision irrigation using boom, we converted the volume of diesel used in the operation into Global Warming Potential (GWP in tCO_2e) (Defra 2013b) and multiplied it by non-tradable prices of carbon (average price over 10 years: 0.06 £ $kgCO_2e^{-1}$) obtained from DECC (2011).

7.4.2.3 Financial and environmental indicators

A discounted cash flow analysis has been carried out, accounting for the social carbon costs in the calculation. It assessed selected economic indicators useful for stakeholders' decision making: Net Present Value (NPV), Internal Rate of Return (IRR), Benefit-Cost Ratio (BCR) and Break-Even Point (B-

E). Other indicators calculated related to the effect of the greenhouse gases, the Global Warming Potential (GWP), as well as some water related indicators defined by Knox et al (2011): Irrigation Supply (IS), Irrigation Use Efficiency (IUE) and Added Value of Water (AVW).

7.4.2.4 Sensitivity analysis

In general, modelling tools are very useful for decision-making but they hide a lot of uncertainty related to the system they represent and associated to the assumptions and method of analysis. Sensitivity analysis can help to determine which parameters are the key drivers of a model's results and to highlight the impact that changes in these parameters will have on the output. In this case, the focus of the sensitivity analysis was to determine the influence on the output y ($y = Benefit\ of\ PI/Benefit\ of\ CI$) of changes in the main input parameter x. For this purpose, we used in a first step the "Bayesian Emulation Machine (GEM), a model based on using the Gaussian process as an emulator (Daneshkhah and Bedford 2013). In a second step, we adopted the traditional method of examining sensitivity based on derivatives of $f(.)$ evaluated at some "base-line" (or central estimate) $x = x_0$, which indicates how the output (y) will change if the base-line input values are slightly perturbed. This method has the advantage of giving a quantitative value of the change in the output (y).

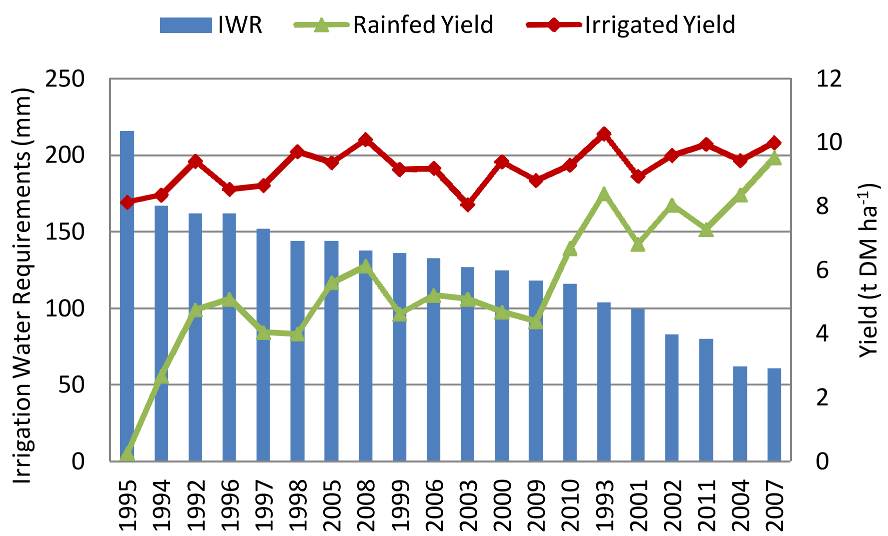
7.4.3 Results

This section includes first the calculation of irrigation water requirements and attainable yield under variable rate and uniform rate of irrigation, then it describes the costs and benefits of these practices compared to the rainfed production and finally we assess the selected economic and environmental indicators. We compare both precision and conventional irrigation against the rainfed production because this gives a clear comparative image of the changes in each irrigation technique, thus is more informative for decision making purposes.

7.4.3.1 Irrigation water requirements and yield

The irrigation water requirements for the 20 crop years (from 1992 to 2011) were modelled ranked and plotted against the rainfed and irrigated yield (Figure 63).

Figure 63 *Modelled IWR (mm) from 1992 to 2011 ranked and plotted against rainfed and irrigated yield (t/ha).*



The analysis is presented for three different types of 'weather year', based on those ranked irrigation needs, plus the 'overall mean' values:

- ‘Wet years’, based on the means of the 25% with lowest irrigation need;
- ‘Normal years’, defined as the means of the central 50% years ranked on irrigation need;
- ‘Dry years’, based on the means of the 25% with highest irrigation need;
- ‘Overall mean’, showing the means calculated across all 50 years.

The modelled irrigation water requirements (IWR) and rainfed and irrigated yields for both precision and conventional irrigation, by IMZ, for each climate year and ‘overall mean’ are shown in Table 25. To estimate actual water applied under conventional irrigation we assumed the modelled requirements for the sandy soil, representing the “driest” part of the field (i.e. with the highest IWR) would be applied to the whole field. In contrast, for precision irrigation we assumed the modelled requirement was applied to each IMZ; the average water need is the sum of the water need per IMZ multiplied by the proportion of the area that that IMZ represents. Only net volumes were considered; inefficiencies and losses were considered to be similar under each system.

Table 25 *AquaCrop simulations for IWRs and estimated yields.*

Conventional Irrigation	**IWR**	**Rainfed Yield**	**Irrigated Yield**
Total Field	**(m^3 ha^{-1})**	**(t ha^{-1})**	**(t ha^{-1})**
Wet Years	1112.0	62.9	74.8
Dry Years	2496.0	26.4	67.5
Normal Years	1795.0	43.0	72.3
Overall Mean	1799.5	43.9	71.7
Precision Irrigation	**IWR**	**Rainfed Yield**	**Irrigated Yield**
IMZ 1 (Sandy Soil)	**(m^3 ha^{-1})**	**(t ha^{-1})**	**(t ha^{-1})**
Wet Years	772.0	61.6	73.7
Dry Years	1718.0	25.9	66.3
Normal Years	1285.0	42.2	71.9
Overall Mean	1265.0	43.0	70.9
IMZ 2 (Sandy Loam)	**(m^3 ha^{-1})**	**(t ha^{-1})**	**(t ha^{-1})**
Wet Years	1112.0	70.7	79.2
Dry Years	2496.0	28.7	71.9
Normal Years	1795.0	47.6	73.5
Overall Mean	1799.5	48.6	74.6
IMZ 3 (Loamy Sand)	**(m^3 ha^{-1})**	**(t ha^{-1})**	**(t ha^{-1})**
Wet Years	956.0	58.2	75.2
Dry Years	2180.0	13.5	68.8
Normal Years	1602.0	36.0	73.4
Overall Mean	1585.0	35.9	72.7
Total Field	**(m^3 ha^{-1})**	**(t ha^{-1})**	**(t ha^{-1})**
Wet Years	850.6	62.9	74.8
Dry Years	1904.0	26.4	67.5
Normal Years	1409.1	43.0	72.3
Overall Mean	1393.2	43.9	71.7

The modelled yield of the rainfed crop is lowest for the years with highest irrigation need, and hence highest water stress, as expected. The small fluctuations in the irrigated yield partly reflect temperature variations rather than reflecting changes in water stress. As yield increase was not one of the main objectives in this study, the attainable yield was modelled to be the same under both conventional and precision irrigation for the economic analysis. Any additional yield and/or improved crop quality would be an additional benefit.

The marketable yield was estimated by dividing the dry matter yields (DM) generated by the model by 13%. This value was adopted from Perez Ortola (2013) based on laboratory analysis of onions from the experimental field. The marketable yield was multiplied by the onion price considered at 154.54 £ t^{-1}, which is the average historical market price in the UK between 2003 and 2012 at the farm gate (Defra, 2013a).

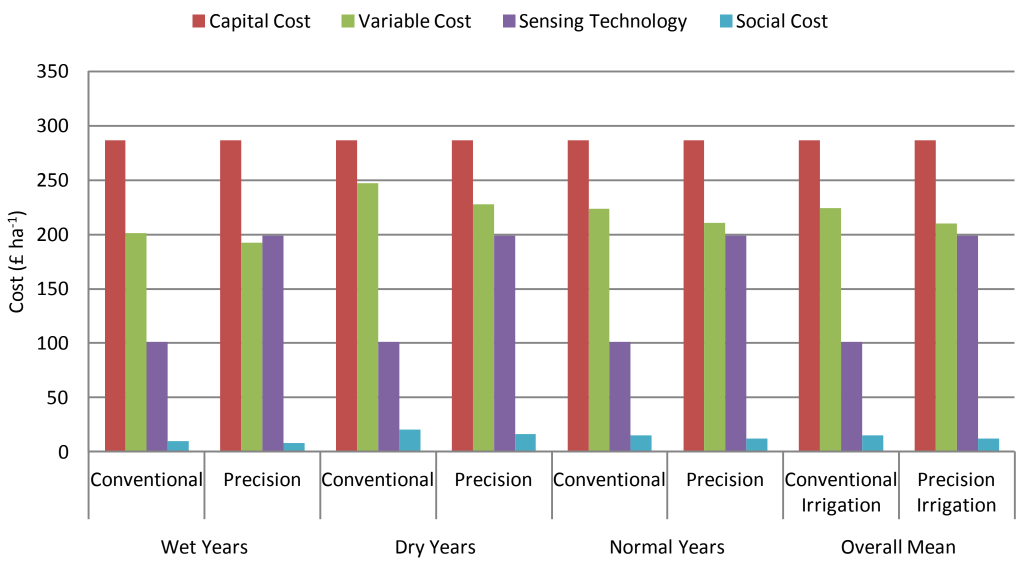
7.4.3.2 Financial investment appraisal

The capital cost of the basic hose-reel irrigation system for conventional irrigation was calculated at 286 £ ha^{-1} when expressed as an annual charge. The sensing technology, control and EMI scanning costs add a further 100 and 199 £ ha^{-1} for CI and PI respectively. The variable costs of the irrigation system (pumping and labour and tractor use) fluctuated between 192 £ ha^{-1} and 247 £ ha^{-1}; in the 'overall mean'it was respectively 223 £ ha^{-1} and 210 £ ha^{-1} for CI and PI. The annual abstraction charges oscillated between 139 £ ha^{-1} and 240 £ ha^{-1}, and in an 'overall mean' year they were 211 £ ha^{-1} and 162 £ ha^{-1} for CI and PI respectively.

The estimated social cost of carbon associated with the "carbon dioxide equivalents" from the irrigation activity (pumping and tractor emissions) varied between 8 £ ha^{-1} and 21 £ ha^{-1} (in the 'overall mean' year: 15.5 £ ha^{-1} CI and 12.4 £ ha^{-1} PI). The variation in the abstraction and the SCC costs reflects both the lower water usage in drier years (the part 2 tariff element) for both systems and the smaller maximum quantity needed for the precision irrigation system, reflected in the lower part 1 tariff.

The total cost is the combination of all costs described above and it was between 598 £ ha^{-1} in 'wet year' to 712 £ ha^{-1} in a 'dry year'. The total irrigation costs for conventional and precision irrigation in the 'overall mean' year are respectively 626 £ ha^{-1} and 695 £ ha^{-1}. Despite the savings in water and energy, the precision irrigation system modelled is more expensive overall. The results also show that capital costs dominate in both systems, in all types of weather year (Figure 64).

Figure 64 *Components of irrigation costs (£ ha^{-1}) for conventional and precision irrigation in different weather years.*



Finally, the costs and benefits of conventional and precision irrigation are compared and the net profits were estimated (Table 26). Results show that the net profits from precision irrigation are still below the profits from conventional irrigation (≈ 0.9% in the 'overall mean' year).

Table 26 *FIA under conventional and precision irrigation.*

Conventional Irrigation (CI)	Wet Years	Dry Years	Normal Years	Overall Mean
Marketable Product (t ha^{-1})	74.8	67.5	72.3	71.7
Price (£ t^{-1})	145.5	145.5	145.5	145.5
Total Benefits (£ ha^{-1})	1790.4	6256.1	4397.9	4210.6
Abstraction charges (£ ha^{-1})	183.1	240.2	211.3	211.5
Irrigation Cost (£ ha^{-1})	487.2	533.5	510.1	510.2
Social Cost (£ ha^{-1})	10.2	20.8	15.4	15.5
Total Costs (£ ha^{-1})	781.5	895.5	837.8	838.1
Profits from CI (£ ha^{-1})	**1008.9**	**5360.6**	**3560.2**	**3372.5**
Precision Irrigation (PI)	**Wet Years**	**Dry Years**	**Normal Years**	**Overall Mean**
Marketable Product (t ha^{-1})	74.8	67.5	72.3	71.7
Price (£ t^{-1})	145.5	145.5	145.5	145.5
Total Benefits (£ ha^{-1})	1790.4	6256.1	4397.9	4210.6
Abstraction charges (£ ha^{-1})	139.8	183.2	162.8	162.2
Irrigation Cost (£ ha^{-1})	478.5	513.7	497.2	496.6
Sensing Technology	198.6	198.6	198.6	198.6
Social Cost (£ ha^{-1})	8.2	16.3	12.5	12.4
Total Costs (£ ha^{-1})	825.1	911.8	858.6	869.7
Profits from PI (£ ha^{-1})	**965.4**	**5344.3**	**3539.4**	**3340.9**
FIA – PI/CI (£ ha^{-1})	**-43.6**	**-16.3**	**-20.8**	**-31.6**

7.4.3.3 Financial and environmental indicators

The selected financial and environmental indicators were calculated (Table 27). Even though the financial indicators showed a slight advantage of conventional irrigation, the environmental indicators showed clearly the positive externalities generated using precision irrigation compared to conventional irrigation, reflecting the reduced water usage. The added value of water on the onions seems to be slightly higher than the value calculated by Morris et al (2003) at around 1.6 £ m^{-3} for a potato crop in the UK.

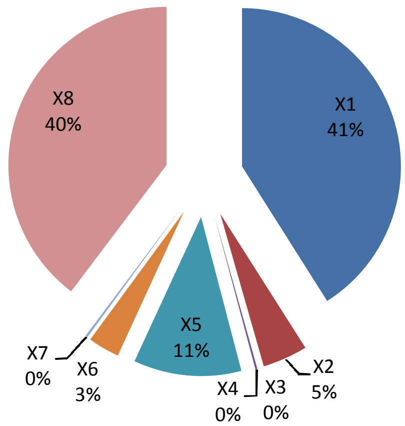
Table 27 *Selected indicators for conventional and precision irrigation in an 'overall mean' year.*

Indicators	Conventional	Precision
Net Present Value (NPV) – (£ ha^{-1})	31,489.8	31,431.8
Internal Rate of Return (IRR) – (%)	195	178
Benefit-Cost Ratio (BCR)	9.9	9.8
Break-Even Point (B-E) – (ha)	18.2	22.7
Irrigation Supply (IS) – (m^3 ha^{-1})	1799.5	1393.2
Irrigation Use Efficiency (IUE) – (t m^{-3})	0.007	0.009
Added-Value of Water (AVW) – (£ m^{-3})	1.9	2.4
Global Warming Potential (GWP) – (tCO_2e ha^{-1})	7.5	5.9

7.4.3.4 Sensitivity analysis

In a first step, the "Bayesian Emulation Machine (GEM) modelled variance of the output (y) with respect to the input variables; taking into account only the inputs that could change the total economic output between the two irrigation techniques (e.g. market price of onion was not considered in the sensitivity analysis because it will change evenly in conventional and precision irrigation). The parameters that have a high impact on (y) are yields, water charge, variable costs of irrigation systems and social carbon cost (Figure 65).

Figure 65 *Influence of input parameters on the economic output.* X1: Rainfed Yield; X2: Irrigated Yield; X3: Weather Years; X4: Soil Variability; X5: Water Charge; X6: Variable Cost; X7: Sensing Technology Cost; X8: Social Cost.



The second step in the sensitivity analysis tested the relationship between output (y), and each of the inputs described above that have impact on the benefits. The results showed that benefits are very elastic to irrigated yield change and less elastic to rainfed yield (Table 28), while they revealed rigidity to the variable cost of irrigation systems (changing variable costs $\pm$ 25%, 50% and 75%: $-1.18\% < y < -0.67\%$), the social carbon cost and abstraction charges (Table 29). Indeed, a $\pm$ 5% change in irrigated yield would generate a substantial variation in benefits ($-16.4\% < y < 14.5\%$), similarly, $\pm$ 25% change in the cost of abstraction charge would vary the benefit by approximately $\pm$ 0.35%.

Table 28 *Sensitivity of output ($y = Benefit\ Precision/Benefit\ Conventional$) to irrigated and rainfed yield in a 'overall mean' year.*

Rainfed Yield (t ha^{-1})	Irrigated yield (t ha^{-1})						
	– 15%	– 10%	– 5%	71.7	+ 5%	+ 10%	+ 15%
– 10%	–40.0%	–26.9%	–13.9%	–0.8%	12.3%	25.3%	38.4%
– 5%	–43.4%	–29.2%	–15.0%	–0.9%	13.3%	27.5%	41.6%
42.8	–47.4%	–31.9%	–16.4%	–0.9%	14.5%	30.0%	45.5%
+ 5%	–52.2%	–35.1%	–18.1%	–1.0%	16.0%	33.1%	50.1%
+ 10%	–58.1%	–39.1%	–20.1%	–1.2%	17.8%	36.8%	55.8%

Table 29 *Sensitivity of output ($y = Benefit\ Precision/Benefit\ Conventional$) to technology and social costs.*

Social Cost (£ ha^{-1})	Cost of Abstraction Charge (£ ha^{-1})						
	– 75%	– 50%	– 25%	198.6	+ 25%	+ 50%	+ 75%
– 50%	–1.98%	–1.66%	–1.33%	–0.98%	–0.63%	–0.26%	0.12%
– 25%	–1.96%	–1.64%	–1.30%	–0.96%	–0.60%	–0.24%	0.14%
12.3	–1.94%	–1.62%	–1.28%	–0.94%	–0.58%	–0.21%	0.17%
+ 25%	–1.92%	–1.60%	–1.26%	–0.92%	–0.56%	–0.19%	0.19%
+ 50%	–1.90%	–1.58%	–1.24%	–0.89%	–0.54%	–0.17%	0.22%

Table 30 *Sensitivity of the output to soil variability.*

Case	Soil variability	y
Case 1	IMZ 1: 70%, IMZ 2: 15% and IMZ 3: 15%	−1.4%
Case 2	IMZ 1: 15%, IMZ 2: 70% and IMZ 3: 15%	−2.6%
Case 3	IMZ 1: 15%, IMZ 2: 15% and IMZ 3: 70%	−1.7%
Case 4	IMZ 1: 33.3%, IMZ 2: 33.3% and IMZ 3: 33.3%	−1.8%
Case 5	IMZ 1: 100%, IMZ 2: 0% and IMZ 3: 0%	−2.9%
Case 6	IMZ 1: 0%, IMZ 2: 100% and IMZ 3: 0%	−3.3%
Case 7	IMZ 1: 0%, IMZ 2: 0% and IMZ 3: 100%	−2.2%
Case 8	IMZ 1: 50%, IMZ 2: 25% and IMZ 3: 25%	−1.6%
Case 9	IMZ 1: 25%, IMZ 2: 50% and IMZ 3: 25%	−2.2%
Case 10	IMZ 1: 25%, IMZ 2: 25% and IMZ 3: 50%	−1.8%

The final sensitivity analysis was to test the output (y) response to change in soil variability because much of the literature reviewed suggests a correlation between viability of PI and soil variability (Almas *et al.,* 2003; Marek *et al.,* 2001). Thus, the model was run several times with different soil combinations and benefits were calculated (Table 30). Even though the ratio of change is not significant, the result shows that benefits are directly related to soil variability. Indeed the higher the homogeneity (Cases 5, 6 and 7) the lower the benefit ratio; therefore the lowest the precision irrigation benefits compared to conventional irrigation. Conversely, higher soil variability increases the precision irrigation benefits compared to conventional irrigation (Cases 1, 3 and 8).

7.4.4 Discussion

At present, the net advantage adopting precision irrigation is in terms of CO_2e emissions considerably lower in the case of PI compared to the conventional irrigation (GWP of PI is approximately 20% lower compared to CI). The other advantage is in water saving as in an average year and under the same conditions, over 400 m^3 ha^{-1} (≈22% compared to CI) could be saved using the smart technology to irrigate onions. These results are in accordance with Evans and King (2012) who reported water savings of 0% to 26% from different case studies across the USA, it also agrees with the conclusions of Al-Kufaishi *et al* (2006) who showed under similar climate conditions that precision agriculture is the best option for water conservation as it saved in the 2003/04 season between 131.6 m^3 ha^{-1} and 299.6 m^3 ha^{-1} under different water scheduling in a sugar-beet field in Germany. However, the financial appraisal results (Table 26) showed that profits of conventional irrigation in average are still slightly higher than precision irrigation, but this varies depending on the weather year:

- In 'wet years' $PI - CI = -43.56\ £\ ha^{-1}$.
- In 'dry years' $PI - CI = -16.3\ £\ ha^{-1}$.
- In 'normal years' $PI - CI = -20.8\ £\ ha^{-1}$.
- In 'overall mean' years $PI - CI = -31.6\ £\ ha^{-1}$

This analysis does have limitations. Firstly, the AquaCrop model does not consider yield reduction due to water stress from over-irrigation, as would occur in some parts of the conventionally irrigated field. We have not considered additional management costs; these should be fairly minor for a system that responds only to the pre-mapped IMZs, whereas some more interactive precision systems could have significant additional management costs. A more fundamental limitation, which also applies to all the previous modelling studies, is that the conditions and the irrigation within each IMZ have been assumed to be perfectly uniform. In practice, there will still be non-uniformity in the field, it is impossible to apply irrigation perfectly uniformly, and the sensing and hence scheduling cannot be perfectly accurate. Together, these limitations may reduce the advantages of precision irrigation, though it is very difficult to estimate by how much.

In this study, the attainable yield was modelled to be the same under both CI and PI. Nevertheless, Lu et al (2005) showed in South Carolina (USA) under PI that corn yield could increase between 1.7% and 2.2% depending on the irrigation scheduling compared to CI; and Simmonds et al (2013) estimated a 7.1% to 14.5% increase in rice systems under precision management in California (USA). A similar increase would definitely make PI in this case study financially viable according to the sensitivity analysis in Table 28. This, without even accounting for the quality improvement in the production as Morris et al (2014) showed that quality improvement could generate two-fold revenue in the irrigated horticulture in the UK. Furthermore, the study did not consider the extra-benefits that precision irrigation could generate due to the optimisation of IWRs and the prevention of water stress (under-watering or over-watering) in different zones of the field. This obviously could vary with the level of variability and the crop under consideration. Another aspect that could be discussed is the importance of farm reservoirs in UK agriculture that has been discussed in the literature (Morris et al 2014). If we only consider the capital cost of a reservoir equivalent to 0.18 £ m^{-3} of stored water per 400 m^3 ha^{-1} of water saved in PI compared to CI this would make a £72 ha^{-1} additional saving in PI which would change the appraisal of the investment.

7.4.5 Summary

The study integrated modelling tools to simulate the benefits of precision irrigation (PI) and conventional irrigation (CI), and compare them to the rainfed production, for an onion crop grown in a typical temperate climate (East of England, UK) using a hose-reel fitted with a boom system. Aquacrop simulated IWRs and corresponding yields for three different soil types (Sandy, Sandy Loam and Loamy Sand). We considered three IMZ in the field (not optimised) and weighted the IWRs and yields with the corresponding percentage areas. Overall, although the precision irrigation system modelled leads to significant water savings and energy efficiency benefits, these alone do not cover the additional costs. However, crop yield or quality benefits, higher water costs (or values) and/or greater soil variability would make investment in precision irrigation more viable. Optimisation of the precision irrigation system management could also give significant improvements. Given the promising environmental benefits in terms of water saving and CO_2 emission reduction, more studies are recommended to first to respond to the unanswered questions and reduce the limitations and to give precise answer to farmers who are the potential users of this technology in the future, and finally to policy makers who are obliged under the EU Water Framework Directive (EU-WFD) to implement measures in order to reduce water use.

The potential economic benefits from PI for supplemental irrigation on field-scale crops in a humid climate such as England appear modest. The benefit to the grower in the reduced cost of water and energy is estimated to be typically less than £25 per hectare that is over-irrigated. Clearly the development and uptake of PI would need to be justified more in terms of the wider benefits to crop quality (reducing variability in crop samples) and the reduced environmental impacts associated with irrigation (reduced drainage and higher nitrogen use efficiency). Further work is however required to assess these under real situations and to provide quantitative evidence to substantiate preliminary evidence regarding the agronomic (yield) benefits of precision irrigation.

8. Knowledge transfer and dissemination

8.1 Activities and beneficiaries

This project has provided multiple opportunities for the research outputs and benefits to flow from collaboration between the academic and industry partners. The key activities that have supported industry knowledge transfer have included technical meetings, on-farm demonstrations/field visits, farmer workshops and training events, publishing information booklets and industry articles, and organising a major industry conference at the end of the project.

These have provided excellent opportunities for presenting the scientific approaches and key findings from the research, demonstrating technical developments and their in-field application, publishing information to highlight new research, developments and grower options, promoting research through trade and industry media and sharing knowledge through the end of project conference.

The beneficiaries from these KT activities have included growers and businesses directly involved in the Hortlink project, other growers, industry companies, farmer organisations, crop sector organisations (e.g. BCGA, BLSA), the water regulatory authority (EA), UK levy boards (AHDB HDC and PCL) and stakeholders with interests in food production, water and environmental management (e.g. retailers). The range of KT activities undertaken during the project targeted to growers, the agri-food industry and science community are briefly summarised below:

8.2 Technical and conference presentations

A summary of the many technical and conference presentation made by the research staff during the project are summarised below:

- Presentation by Knox at Irrigation Research Day, Lancaster University (March 2010);
- Presentation by Knox at NFU Water Summit, Newmarket (Nov 2010);
- Presentation by Knox at Warwick Water Day "Precision irrigation scheduling: integration of new technologies, Warwick HRI, Wellesbourne (Sept 2010);
- Presentations by Monaghan and Grove to growers as part of a LEAF Technical Open Day at Harper Adams University (April 2011);
- Presentation by Knox at UK Vegetable Industry Conference organised by Syngenta/ADAS, Peterborough (February 2011);
- Presentation by Knox at Defra/PCL Potato Research Day, Stoneleigh (Jan 2011);
- Presentation by Knox to Sainsbury Grower Meeting, Cambridge (May 2011);
- Presentation by Knox to Waitrose Technical Meeting, Kent (June 2011);
- Presentation by Monaghan to LEAF Innovation Day, Shropshire (July 2011);
- Presentation by Monaghan at Research Seminar, Bologna University, Italy (July 2011);
- Presentation by Monaghan to BLSA Technical Committee, Shropshire (Sept 2011);
- Presentations by Monaghan and Knox at Cropworld 2011 Conference London (Nov 2011);
- Presentation by Daccache at 1st CIGR Inter-Regional Conference on Land and Water Challenges, Bari (Italy) (10 September 2013);
- Presentation by Daccache and Knox at AATP Soil and Water Management Workshop, Gs Cambridge (July 2013).
- Presentation by Daccache at AATP Precision Farming Technology, Harper Adams (February 2014);

- Presentation by Daccache and Hess “Conventional versus precision irrigation - scheduling and engineering challenges” at *Precision Irrigation: Current progress and future challenges,* UK Irrigation Association (UKIA) Annual Conference, Peterborough (6th March 2014);
- Presentation by Monaghan “Maximising yield and crop quality under precision irrigation” at *Precision Irrigation: Current progress and future challenges,* UK Irrigation Association (UKIA) Annual Conference, Peterborough (6th March 2014);
- Presentation by Francis “Elveden Estate: practicalities implementing precision irrigation” at UK Irrigation Association (UKIA) Annual Conference, Peterborough (6th March 2014);
- Presentation by Daccache at AATP Precision Farming Technology, Harper Adams (June 2014);

8.3 Science publications

- Perez-Ortola, M., Daccache, A., Hess, T.M., and Knox, J.W (2014). Simulating impacts of irrigation heterogeneity on onion (Allium cepa L.) yield in a humid climate. *Irrigation Science* Doi: 10.1007/s00271-014-0444-2.
- Daccache, A, Knox, J.W., Weatherhead, E.K., Daneshkhah, A, and Hess, T.M. (2014). Implementing precision irrigation in a humid climate: recent experiences and on-going challenges *Agricultural Water Management* Doi: 10.1016/j.agwat.2014.05.018.
- Perez-Ortola and Knox, J.W (2014). Water relations and irrigation requirements of onion (Allium Cepa L.): a review of yield and quality impacts. *Experimental Agriculture* Doi: 10.1017. S0014479714000234.
- Knox, J.W., Weatherhead, E.K., Hess, T.M. and Daccache A. (2014). Integrating biophysical and ballistics models to assess agronomic and environmental impacts of precision irrigation on crop yield. *Environmental Modelling and Software* (under review).
- Monaghan, J.M., Daccache, A., Vickers, L., Hess, T.M., Weatherhead, E.K., Grove, I.G., Knox, J.W. (2013). More ‘crop per drop’ – constraints and opportunities for precision irrigation in European agriculture. *Journal Science of Food and Agriculture* 93(5):977-80.
- El Chami D., Knox JW, Daccache A., and Weatherhead, EK (2014) Assessing environmental cost-benefits of precision irrigation using a travelling hose-reel irrigator with a boom in a humid climate – A study in the East of England. *Precision Agriculture* (submitted).

8.4 Industry publications

Knox, J.W (2014) “Water for where and when it’s needed” HDC News March 2014 pp15-17.

Knox, J.W., Daccache, A., Hess, T.M, and Weatherhead, E.K. (2014) *Precision Irrigation. Assessing the technical, agronomic, and engineering challenges for UK field-scale agriculture and horticulture*. An Information Booklet for growers. Cranfield University

HDC News An article on the project appeared in HDC News (May 2012).

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