Cranfield UNIVERSITY

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

Year 2 Annual Report (A1)
Defra Hortlink HL0196

28th August 2012

J.W. Knox, A. Daccache, T.M. Hess and E.K.Weatherhead (Cranfield University)

J. Monaghan and I. Grove (Harper Adams)

B Davies (Lancaster University)

Project partners

This project (HI0196) is funded by Defra under their Hortlink programme . It is supported by the following academic and industry organisations:

Cranfield UNIVERSITY

LANCASTER UNIVERSITY

Harper Adams UNIVERSITY COLLEGE

NATURALLY G's FRESH

ELVEDEN ESTATE

PDM natural freshness · real taste PDM PRODUCE (UK) LTD

ADCON TELEMETRY

plantsystems Crop Consultants

Wroot Water Limited

UK

BRIGGS IRRIGATION

HDC

Vegetable Consultancy Services Ltd
Comprehensive Agronomy Support for the Vegetable Industry

Table of Contents

ACKNOWLEDGEMENT **6**

1 PROJECT SUMMARY YEAR 2 .... **7**

2 FIELD EXPERIMENTS **8**

2.1 Site selection 8
2.2 Methods and field data 9
2.2.1 Using electromagnetic induction (EMI) for scanning in-field soil variability 9
2.2.2 Visible and Near Infrared Spectrometry (Vis-NIR) 11
2.2.3 Laboratory analysis 13
2.2.4 Wireless soil moisture network 15
2.2.5 Performance assessment of the irrigation systems 16
2.3 Results and discussion 17
2.3.1 Soil variability 18
2.3.2 Soil moisture sensors 22
2.3.3 Irrigation uniformity 24
2.3.4 Observed variability in crop yield 26

3 POLYTUNNEL EXPERIMENTS **29**

3.1 Onions (HortOnion01) 29
3.1.1 Materials and methods 29
3.1.2 Results: soil moisture variation 31
3.1.3 Results: crop water status (high OM only) 34
3.1.4 Results – Crop growth 35
3.1.5 Results – Harvest 35
3.2 Lettuce (HortLet02) 37
3.2.1 Materials and methods 37
3.2.2 Results – Soil moisture variation 39
3.2.3 Results: crop water status (High OM only) 41
3.2.4 Results – Crop growth 42
3.2.5 Results – Harvest 42
3.2.6 Results – Post harvest 45
3.3 Lettuce (HortRhizo01) 46
3.3.1 Materials and methods 46
3.3.2 Results: soil moisture variation 47
3.3.3 Results – root growth 47

4 SUMMARY AND CONCLUSIONS **50**

5 REFERENCES **51**

List of Figures

Figure 1 Location of three grower field sites used in 2011. 8

Figure 2 Temperature (Degree C) and rainfall (%) anomalies in 2011 compared to the long term average (1961-1990) across England. 9

Figure 3 Geonics EM38 scanner used in this project with horizontal and vertical coil orientation. 10

Figure 4 Conducting an EMI soil survey using a Geonics EM38 scanner attached to a GPS at Elveden in March 2011. 11

Figure 5 On-line vis-NIR spectroscopy based sensor used in March 2011 at Ely, Elveden and Shropshire field sites. 12

Figure 6 Schematic illustration of steps used for on-Vis-NIR line measurement and mapping of soil properties. 13

Figure 7 USDA soil texture classification triangle. 14

Figure 8 Tensiometers (onions) and Adcon capacitance probes (lettuces) used in the field experiments in 2011. 15

Figure 9 Short (A733 addWAVE) and long range (RA440) remote telemetry unit and solar panels used to power the wireless soil monitoring devices in 2011. 16

Figure 10 Wireless soil water monitoring system installed at Elveden and Ely field sites. 16

Figure 11 Conducting irrigation uniformity tests at Ely and Elveden field sites in 2011. 17

Figure 12 Organic carbon content (a) and percentage of soil samples in each textural class (b) at each farm site. Error bars represent range of variation between soil samples. 18

Figure 13 Spatial variation of apparent electrical conductivity (ECa) measured using the EMI scanner at (a) Ely (b) Elveden and (c) Shropshire field sites. 19

Figure 14 On-line reflectance spectra observed for the field site at Ely. 20

Figure 15 Model predicted and observed values for organic carbon (OC) and moisture content (MC) at (a) Ely (b) Elveden and (c) Shropshire field sites in 2011. 20

Figure 16 Derived soil moisture content maps using the online vis-NIR sensor at Ely, Elveden and Shropshire field sites. 21

Figure 17 Derived organic carbon content (%) maps using the online vis-NIR sensor at Ely, Elveden and Shropshire field sites. 21

Figure 18 Capacitance probe (averaged over 10, 20 and 30 cm depths) and rain gauge measurements from four different blocks (A, B, C and D) at the Ely field site. 22

Figure 19 Matric potential measured using 3 tensiometers (at different depths 15, 30 and 45 cm) in each block (A, B, C, and D) at the Ely field site. 23

Figure 20 Capacitance probe volumetric water content (averaged 10, 20 and 30 cm) and rain gauge measurements at Elveden field site. The second y-axis represents water applied (mm) by irrigation and/or rainfall. 23

Figure 21 Relative soil water content measured using 4 moisture probes at Elveden farm site. 24

Figure 22 Uniformity of water application under the boom system on lettuces at Ely in 2011. Error bars represent the range of variation between two uniformity test measurements. 25

Figure 23 Probability of exceedance for the depth of irrigation water applied by the hosereel and boom system on lettuces at the Ely field site, based on data for 2011. 25
Figure 24 Uniformity of water application on 2nd and 15th August 2011 at the Elveden field site. 26
Figure 25 Probability of exceedance for the depth of irrigation water applied by the hosereel and boom system on onions at the Elveden field site, based on data for 2011. 26
Figure 26 Measured mean fresh and dry weight (g/head) of lettuce heads harvested in each block at Ely field site in 2011. 27
Figure 27 Measured bulb fresh weight (g/bulb) and diameter (cm) of onions harvested in each block at Elveden Estate (Suffolk). 28
Figure 28 Hortonion01 – experimental site under the polytunnel at HAUC (Summer 2011)...............29
Figure 29 SMD during experiment a) high organic matter soil; b) low organic matter soil..................32
Figure 30 Total water loss calculated from weekly differences in soil moisture deficit (SMD). 34
Figure 31 Relationship between stomatal conductance and SMD..34
Figure 32 Average bulb yield per bin (fresh weight g)..35
Figure 33 HortLett02 – experimental site at HAUC in Summer 2011. 38
Figure 34 SMD over time of experiment (a) high organic matter soil and (b) low organic matter soil. 40
Figure 35 Total water loss (mm) calculated from weekly SMD differences..41
Figure 36 Stomatal conductance on SMD at 10 cm...42
Figure 37 Average total biomass per plant (FW plant^{-1}). 43
Figure 38 Marketable yield expressed as average individual head fresh weight (g FW plant^{-1}). 43
Figure 39 Head moisture content (%) for the low and high organic matter treatments......................44
Figure 40 Relative head water content of the outer leaves 20 days after harvest. 45
Figure 41 Total SMD over the experiment. 47
Figure 42 Average days for first root to attain depth. 48
Figure 43 Hortrhizo01 showing (a) face of rhizotron with cover removed and (b) rear of rhizotron with covered access holes. 48
Figure 44 Number of roots observed down the rooting profile in rhizotron grown lettuce. 49

List of Tables

Table 1 Summary model validation results for organic carbon (OC) and moisture content (MC). 20

Table 2 Yield variation for lettuce (circumference, total, head and waste fresh weight) between blocks (A to D) for Ely field site in 2011..........27

Table 3 Unamended polytunnel soil properties used for the experimental fieldwork in 2011. 30

Table 4 Experimental design and layout for 2011 polytunnel fieldwork. 30

Table 5 Accumulated loss of water (mm) from the wheelie bins during experiment. 33

Table 6 Total water applied and irrigation water use efficiency (IWUE) (g l^{-1}). 36

Table 7 Experimental design and layout 37

Table 8 Accumulated loss of water (mm) from the bins over the experiment. 40

Table 9 Total water applied (l/bin) and Irrigation WUE (g l^{-1}) for both biomass and head fresh weight..........45

Table 10 Experimental treatments and layout. 46

Acknowledgement

This project team acknowledge Defra for their continued financial support. In addition, the authors acknowledge the following individuals and organisations for their specific contributions to the project in Year 2:

- David Cole and Robert Montgomery (Hortlink Monitoring Officer) for their project support and guidance;
- Ed Moorhouse (G's) for his project industry leadership;
- Andrew Francis and Ian Robertson (Elveden Estate) for their support and advice regarding onion production;
- Will Forbes and Liz Johnson (G's) and Dermott Tobin (PDM Produce) for their support and advice regarding lettuce production;
- Anthony Hopkins (Wroot Water Systems) for supplying sprinkler irrigation equipment
- Bernhard Pacher (Adcon Telemetry) for his technical support and provision of soil moisture monitoring equipment;
- James and David Martin (Plantsystems) for their technical support regarding wireless soil moisture sensing;
- Melvyn Kay (UK Irrigation Association) for promoting the research and knowledge transfer to growers;
- Tim Lacey (VCS) for technical contributions and advice regarding onion agronomy, and;
- Richard Earl and staff at Turftrax Ground Management Systems for technical assistance with the EMI scanning equipment.

1 Project summary Year 2

The second year of the project has focused on conducting field experiments initiated on grower sites in Year 1. An intensive campaign of fieldwork has been undertaken by research staff from Cranfield University on three different fields at G's (Ely), Elveden Estate (Thetford) and PDM (Shropshire) on lettuces and onions. At the same time, research staff at Harper Adams University College (HAUC) and Lancaster University have been conducting detailed controlled experimental crop growth and irrigation trials on lettuce and onions under polytunnels at HAUC.

The spatial variabilities in soil at each grower field site have been mapped and assessed using an electromagnetic induction scanner (EMI). This has proven to be a quick, cost effective and efficient method to identify zones of variability within individual fields, but the technique is limited in terms of its ability to explain the reasons for soil variability (texture, bulk density, moisture content, organic content etc). A new and promising technique has been tested at each of field site in order to try and understand the main factors influencing soil variability. A visible and near infra-red (Vis NIR) spectrophotometer mounted on an agricultural implement has been used to collect spectral signature data for each field. The spectral data and laboratory analyses of 30 soil samples from each field have then been used to calibrate and validate a model to map the spatial variabilities in clay content, organic carbon and soil moisture content. Further model development is needed but this technique could provide a useful tool in support of mapping soil moisture variability to inform the placement of infield wireless soil moisture sensors.

In selected grower fields, dense arrays of wirelessly capacitance probes and tensiometers have been installed in lettuces at G's (Ely) and onions at Eveden (Thetford). Data on a 15 min time step were collected from these sensors and relayed back over the internet to Cranfield University. Similarly, hourly time step data from an automatic weather station were also collected and relayed. The functionality of this system has been successfully tested and has the potential to provide growers with field scale information on soil moisture status at any time and from any place. Such spatial and real time information will help farm managers make more informed decisions on when, where and how much water might be needed in a particular field.

The performance (uniformity, adequacy and efficiency) of the irrigation application systems used on lettuces (Ely) and onions (Elveden) has been assessed using catch cans. These data are being used to assess the impacts of spatial and temporal water variability on final crop yield. Field samples of lettuce and onion from each of the areas monitored using the soil moisture sensing arrays were harvested and analysed for fresh weight and head/bulb circumference. The field data collected from these grower sites is being compared against crop and yield data collected from the scientifically controlled experimental trials at HAUC. Both datasets will be used to help calibrate and validate suitable biophysical crop models for simulating lettuce and onion growth, yield and quality in 2012.

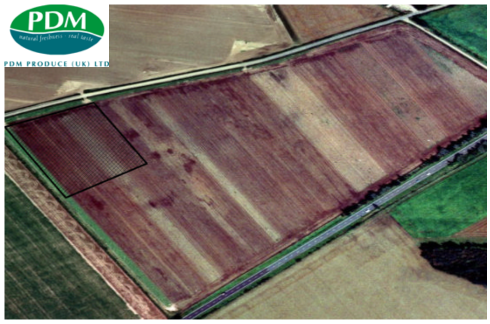
At HAUC, experimental trials have been undertaken to study the effects of soil moisture variability on plant growth, yield and rooting. Soil samples from the polytunnel have been amended with peat to produce two soil types (low organic (5%) and high organic (25%) matter). The lettuce and onion crops were grown in plastic containers and 5 different irrigation treatments imposed. Soil moisture content was measured weekly using a Diviner probe. The irrigation treatments were very wet (90%AWC), wet (66% AWC), moderate (33%AWC) and dry (8% AWC). An automatic weather station was installed in the polytunnel. All data were collected and statistically analysed. In addition, iceburg lettuces (*cv Challenger*) were grown in split rhizotrons using the 25% amended soil (high OM) and two different irrigation treatments (very wet- return to 100%FC and dry -no water added) applied. Soil moisture in each rhizotron was monitored at five depths (20, 40, 65,90 and 110 cm) as well as the rates and distribution of rooting. The lettuce plants produced more, deeper roots in response to a developing soil moisture deficit. Roots were observed at depths >1m in 23 days. The experimental data will also be used to help calibrate the biophysical crop model for lettuce.

2 Field experiments

2.1 Site selection

The experiments in Year 2 (Summer 2011) were conducted on three different sites on commercial farms at Ely (Cambs), Elveden (Suffolk) and Telford (Shropshire) (Figure 1). The site at Elveden (Lat 52° 22’ 55’’N, Long: 0° 36’ 17’’ E) was grown with drilled onions while the other two fields, PDM (Lat 52° 43’ 58’’N, Long: 2° 25’ 43’’ W) and G’s (Lat 52° 28’ 47’’N, Long: 0° 21’ 47’’ E) were cropped with transplanted iceberg lettuce. The main advantage of the lettuce crop is the short growing season which allows multiple field trials to be completed in a single growing season.

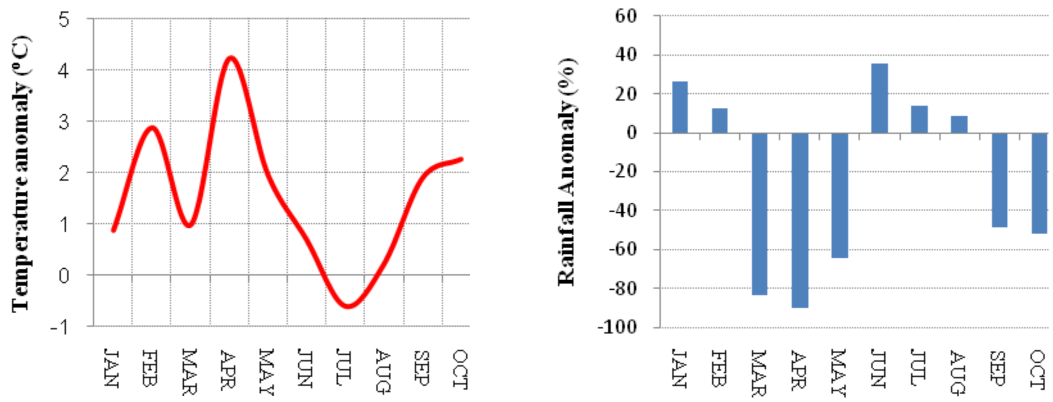
Figure 1 Location of three grower field sites used in 2011.

Geographical location of the 3 sites	Lettuce field site at PDM produce (Telford)
	
Lettuce field site at G’s (Ely, Cambs)	Onion field site at Elveden Estate (Suffolk)
	

The Spring in 2011 (March, April and May) was remarkable for the unusually warm weather in April and lack of rainfall in March and April (Figure 2). The dry weather continued into May in large parts of the country raising widespread concerns regarding water availability for both the environment and agriculture. These very atypical conditions meant 2011 was reported as having the warmest Spring in the last 100 years and driest Spring across England and Wales (shared with 1990).

In contrast, the summer was slightly wetter than the historical long term average (Figure 2) particularly in June. Consequently, the limited water availability caused by the dry Spring was compensated for by these early wet conditions reducing the overalll number of irrigation applications on each crop.

Figure 2 Temperature (Degree C) and rainfall (%) anomalies in 2011 compared to the long term average (1961-1990) across England.



2.2 Methods and field data

Following on from 2010, the field experiments in 2011 focused on assessing crop and irrigation water management practices to help quantify some of the known variabilities (soil texture, soil moisture, water) impacting on the yield and quality of lettuce and onion. In addition, a new methodology to quantify the organic carbon and soil moisture content as well the spatial textural variability of the soil using the visible and near infrared spectrophotometer was tested. The fieldwork in 2011 focused on:

(i) Understanding the inherent spatial variability in soil characteristics using electromagnetic induction (EMI) scanning techniques to map soil variability;

(ii) Quantifying the soil moisture and organic matter content and textural variations of soil using Vis-NIR spectrophotometry;

(iii) Calibration and validation of the Vis-NIR spectrometry data against field soil samples;

(iv) Monitoring the spatial and temporal variabilities in soil moisture status using networks of wireless capacitance probes and tensiometers;

(v) Assessing the spatial and temporal variabilities in irrigation water application under overhead (boom) irrigation, and;

(vi) Measuring the observed variabilities in crop yield within each of the field sites.

A brief description of the research undertaken for each is given below.

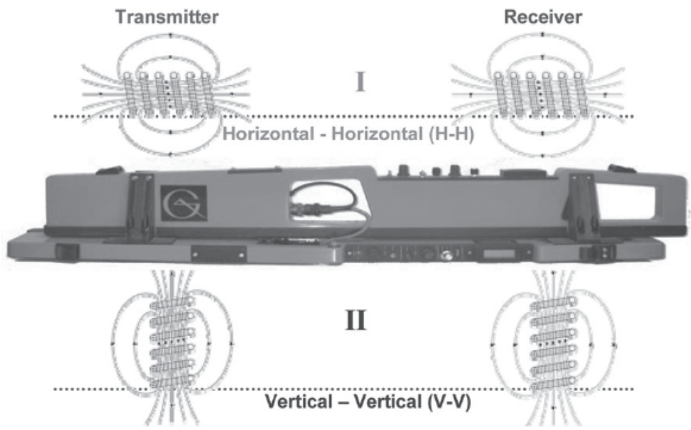
2.2.1 Using electromagnetic induction (EMI) for scanning in-field soil variability

EMI scanning is a proximal, rapid and non-invasive method that been used to obtain information about soil characteristics using surrogate parameters such as the apparent electrical conductivity (ECa) that correlate directly or indirectly with several soil properties (Sudduth et al., 2005). The EMI technique has received considerable attention in precision agriculture research for varying purposes. For example, the EMI technique has been used to identify areas of fields at risk from potential herbicide leaching (Jaynes *et al.*, 1995), to estimate claypan depths (Doolittle et al. ,1994 and Sudduth et al.,2001) and to assess salinity impacts on crop yield (Corwin and Lesch, 2003). Anderson-Cook et al. (2002) found a positive correlation between the apparent electrical conductivity (ECa) measured by an EMI scanner and the previous crop yield. Identifying soil type boundaries (soil texture and moisture content) and mapping crop management zones necessary for precision farming using the EMI technique were reported by Wain *et al*. (2000), James *et al*. (2003), King *et al*. (2005) and Hedley *et al.* (2010).

ECa values can be influenced by several factors, including soil water content, salinity, soil temperature, compaction, texture, organic matter content and mineralogy. In salt affected soils, the solute concentration is the biggest contributor to electrical conductivity (Williams and Hoey, 1987). In temperate climates where salt is not a problem, organic matter and moisture content, mineralogy and soil texture are the main factors affecting ECa values (Brevik and Fenton, 1987). Temperature variations can also have a profound influence on the response of EMI instruments as they are prone to higher marginal error particularly at lower ECa readings. When used to measure soil moisture content it is recommended to carry out the EMI measurement when the soil is equal or higher than field capacity (Godwin and Miller, 2003).

In 2011, EMI surveys were conducted on selected field sites (G's, Elveden and PDM) using 2 Geonics EM38 scanners with different orientations (Figure 3). Each scanner consists of a receiver and transmitter coils separated by a fixed distance. The transmitter coil emits a primary electromagnetic field around it and into the ground. The eddy current induced in the ground based on the soil characteristics is then measured by the receiver coil which registers the corresponding ECa.

Figure 3 Geonics EM38 scanner used in this project with horizontal and vertical coil orientation.



The two different transmitters and receiver coils orientations (Horizontal-Horizontal and Vertical-Vertical) allow soil scanning at different soil depths (Figure 3). The horizontal scanner has the maximum response at 0.4m depth when the instrument is carried about 50 mm above ground (James *et al.,* 2003) while the vertical scanner has a maximum response depth of approximately 1.2m. However, measurement errors caused by moving and carrying the scanner are much reduced with the deeper scan.

The EMI survey was timed to coincide with dry field soil conditions to ensure that the ECa readings were not influenced by soil moisture content but rather reflected inherent variations in soil characteristics. A mobile GPS carried on the back and attached to the scanners was used to geolocate the precise location of each EMI measurement (**Error! Reference source not found.**); hence for each GPS signal, two EMI readings (one from the horizontal and another from the vertical scanner) were registered with the coordinates and stored by a data logger. The GPS scanner system was carried during measurement and moved over each field site in parallel transects.

The field at G's (Ely) was scanned on 8th March, Elveden field on 14th March and Shropshire field on 15th March 2011. The data were processed at Cranfield University, screened, checked and imported into GIS software to produce thematic maps showing the spatial variation in soil at each field site.

Figure 4 Conducting an EMI soil survey using a Geonics EM38 scanner attached to a GPS at Elveden in March 2011.

2.2.2 Visible and Near Infrared Spectrometry (Vis-NIR)

The visible and near-infrared reflectance (Vis-NIR) spectroscopy is a non-contact measurement method which can be used to provide information on soil physical and chemical properties, including organic matter content, soil water content and mineral composition. Vis-NIR spectroscopy is based on the understanding of the interaction between the incident and reflected light characteristics that vary due to the soil surface physical and chemical properties. It is most suited for substances containing the C-H, N-H and O-H molecular bonds as these vibrate when illuminated with light and absorb energy at specific wavebands. Using existing spectral libraries, the soil spectral features can help in understanding the quantitative and qualitative physical-chemical composition of the soil.

Vis-NIR spectroscopy has been used for the assessment of a variety of soil attributes including clay content, pH, organic matter, moisture content, total N and plant-available P (Mouazen *et al*., 2005, 2006a, b, 2007, 2009, 2010; Viscarra-Rossel *et al.,* 2006a, b, 2009; Maleki *et al.,* 2007; Gomez *et al.,* 2008; Viscarra-Rossel and Behrens, 2010; Canasveras *et al.,* 2010; Wetterlind *et al.,* 2010). The online (mobile) vis-NIR system used in this study, consists of a subsoiler that penetrates the soil to the required depth and an optical unit attached to the rear of a subsoiler leg to measure the soil spectra in diffuse reflectance mode. As the implement passes through the soil, the bottom of the trench is smoothed to give better optical measurement by the downward forces of the subsoiler itself. The optical unit is an AgroSpec mobile, fibre type, Vis-NIR spectrophotometer (Tec5 Technology for Spectroscopy, Germany) with a measurement range of 305-2200 nm. The subsoiler is retrofitted with the optical unit and attached to a frame and mounted onto the three point linkage on a tractor.

A differential global positioning system (DGPS) (EZ-Guide 250, Trimble, USA) was used to record the position of on-the-go measurements with sub-metre accuracy. A laptop was used for data logging and communication. The spectrophotometer, laptop and DGPS are all powered by the tractor battery. In each field the travel speed of the tractor and measurement depth were set to 2km/hour and 15 cm, respectively, and the distance between rows was approximately 10m. Ambient light, machine vibration, plant roots, debris and variation of the soil-sensor distance are all factors that can impact on the accuracy of the on-line spectral measurements compared to non-mobile and laboratory measurements. However, the speed of data measurement and the larger spatial resolution of the on-line system offers practicality that can be justified on the grounds of reduced accuracy.

Figure 5 On-line vis-NIR spectroscopy based sensor used in March 2011 at Ely, Elveden and Shropshire field sites.

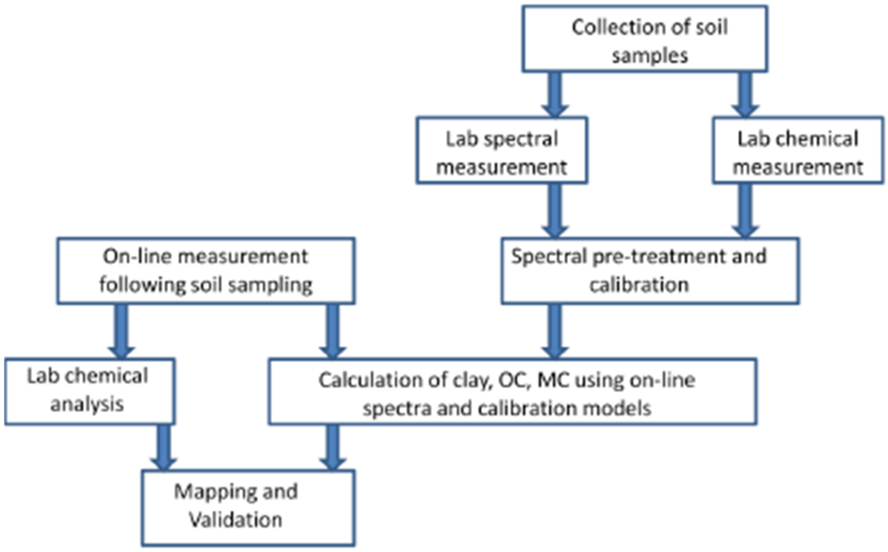
Following the on-line Vis-NIR soil scanning, 35 soil samples were randomly collected from each field in order to calibrate a Vis-NIR model for soil organic carbon and moisture content. Figure 6 provides a schematic representation of the different steps undertaken to map the different soil properties at each of the study sites.

From the 35 soil samples collected at each field, two-thirds of the samples were used for model calibration; the remaining third were used as an independent validation dataset.

For each soil sample used for calibration, the sample was divided equally, with half used to carry out laboratory analysis of soil organic carbon, clay and moisture content and the other half used for optical scanning. The measured spectra and laboratory analysis outputs were then used to develop calibration models for organic carbon and moisture content using a partial least squares regression (PLS).

In order to validate the accuracy of the Vis-NIR system, the values obtained from the laboratory analysis were used as an independent validation dataset and compared against those predicted with the vis-NIR spectra collected at the same point. Coefficients of determination (R^2), Root Mean Square Error (RMSE) and residual prediction deviation (RPD) were used for evaluating the predicted clay, organic carbon and moisture contents from the model.

Figure 6 Schematic illustration of steps used for on-Vis-NIR line measurement and mapping of soil properties.



2.2.3 Laboratory analysis

Soil organic carbon (OC), moisture content and clay content for the 105 soil samples collected from the three field sites were analysed in the soils laboratory at Cranfield. A brief description of the analytical methods is given below.

2.2.3.1 Organic Carbon (OC) analysis

Soil OC was measured according to BS7755 Section 3.8 (BSI, 1995) with a TruSpecCNS spectrometer (LECO Corporation, St. Joseph, MI, USA) using the Dumas combustion method. About 25g of soil was dried in an oven at 105°C for 2hrs ± 10mins. A test portion of 0.001mg was weighed and tightly packed into a small silver-foil capsule. Then 4mol/L hydrochloric acid was added in drops until effervescence stopped. The sample was then dried in an oven at 90°C for 4hrs ± 15 minutes and finally packed into a larger aluminium foil capsule before loading into the carousel of an auto sampler. The test sample mass was entered into the instrument software along with the sample name and the matrix specific oxygen dosing.

2.2.3.2 Moisture content (MC) determination

Soil MC was determined by oven drying the soil samples at 105°C ± 5°C for 24 hours, according to BS7755:1994. The soil moisture content was deduced from the difference in the mass of field-moist soil sample before and after drying.

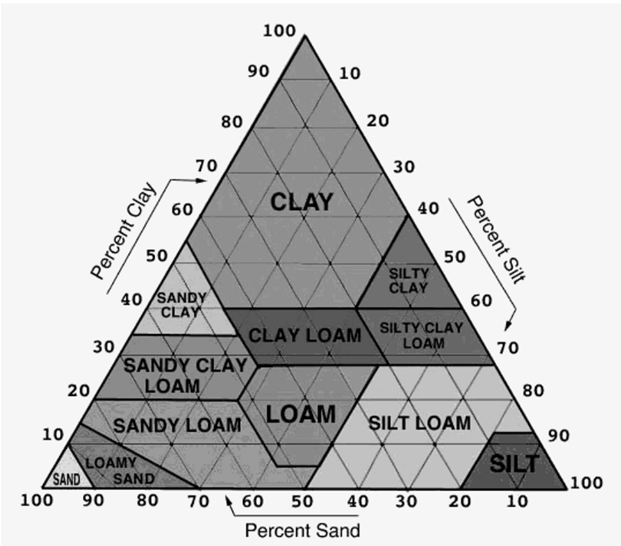
2.2.3.3 Soil texture analysis

Soil texture was measured using the sieving and sedimentation method, according to BS7755 Section 5.4 (BSI, 1998). A brief explanation of this method is given below:

1. *Organic matter removal:* Approximately 10 ml of air-dry, <2 mm soil was placed in a labelled polycarbonate bottle. Using a measuring cylinder, 30 ±1 ml of water was added to each sample, and 25 ±2.5 ml of 100 volume hydrogen peroxide added. The mixture was manually mixed. The bottle was then placed on a cold hotplate in a fume hood overnight. But, no vigorous frothing was allowed to form in the very first few hours after mixing. Afterwards, the temperature of the hotplate was then raised to 100 ± 2°C for about 2 hours. When decomposition is completed, the bottle is removed from the hotplate and allowed to cool.

2. *Dispersal and wet sieving:* The content of the bottle was made up to 200 ± 1g with demineralised water, capped and shaken vigorously to re-suspend, and then centrifuged at 2000 ± 100 rpm for 20 minutes; the supernatant was discarded. Using a dispenser, 20 ±2ml of buffered sodium hexametaphosphate dispensing solution was added, 150 ± 2ml water, using a measuring cylinder was also added and bottles capped and shaken overnight (18 hours) in an end-over-end shaker. Also, 20 ±2ml buffered sodium hexametaphosphate in a weighed bottle was dried in an oven at 105°C overnight. After cooling in a desiccator, the bottle was reweighed. The content of the bottles was gently washed through a 0.063 mm sieve into a 500ml measuring cylinder with water and the residue retained. The residue was dried at 105 ^{o}C ±2°C for a minimum of 4 hours.
3. *Dry-sieving the sand fraction:* The content of each beaker was sieved through a nest of sieves on a sieve shaker for 15 minutes. The mass of each full sieve was recorded and transferred to the respective cylinder and made up to 500 ml with demineralised water.
4. *Determination of silt and clay fractions by pipette extraction:* The cylinders were placed in a water bath and allowed to equilibrate at 25 °C overnight before sampling. Two sets of glass bottles were weighed to receive the 0.002 – 0.063 mm range and <0.002 mm range of particles, respectively. The cylinder was gently stirred for approximately 30 seconds and 25 ml aliquot immediately drawn from the 10 cm depth into the 0.002 – 0.063 mm range bottle. After a sedimentation period of 6 h for the 0.002 mm particle has elapsed, another 25 ml aliquot was drawn at the 9 cm depth into the 0.002 mm range bottle. The sample bottles were then dried at 105°C ± 2°C for a minimum of 24 hours cooled in a desiccator and weighed.
5. *Soil texture classification*: The United States Department of Agriculture (USDA) classification (Figure 7) was used to assess soil texture of each sample to determine sand, silt and clay content.

Figure 7 USDA soil texture classification triangle.



2.2.3.4 Optical measurement

Prior to optical scanning, each soil sample was put in a glass container and mixed. Stones and plant residue were removed to reduce the optical interference and measurement biases. Each soil sample was placed into three petri dishes, shaken and pressed gently before levelling. A smooth soil surface ensures maximum light reflection and high signal to noise ratio (Mouazen et al., 2005). The soil samples were scanned with the same AgroSpec vis-NIR spectrophotometer used during on-line field measurement (Tec5 Technology for Spectroscopy, Germany). A 100% white reference was used before scanning and repeated each 30 min to reset the optical instrument. 10 scans were completed for each soil and averaged in one spectrum. The average spectrum was used to build and upgrade clay, soil moisture and organic carbon content.

2.2.4 Wireless soil moisture network

2.2.4.1 Soil moisture sensors

The gravimetric soil moisture measurement (Section 2.2.3.3) is a direct and accurate method to determine soil moisture content but it is a destructive and time consuming method. Therefore, laboratory measurements cannot be used to monitor soil moisture in real time nor to schedule irrigation practices. Alternatively, soil moisture content can be assessed indirectly by measuring other parameters, the most commonly used are the soil matric potential and soil permittivity. The former is measured by tensiometric methods (tensiometers) while the latter uses dielectric methods (capacitance probes). These two combined indirect soil moisture measurement instruments (Figure 8) were used on the lettuces (Ely) and onion (Elveden) crops. A brief description of these indirect soil moisture measurement methods is provided in the first Milestone Report.

At Ely (lettuce), four monitoring areas were defined representing different management/soil variable zones according to the ECa values produced by the EMI scanning. Each area contained 5 Adcon capacitance probes, 3 tensiometers and 1 rain gauge. The capacitance probes monitored moisture content and soil temperature at 10 cm, 20 cm, 30 cm and 40 cm. The tensiometers measured soil matric potential at 10 cm, 20 cm and 30 cm.

At Elveden (onion) due to the relatively uniform sandy soil, only 4 capacitance probes were installed to monitor moisture content and soil temperature at 4 different soil depths. A rain gauge was also installed to monitor rainfall and the amounts of water applied by irrigation.

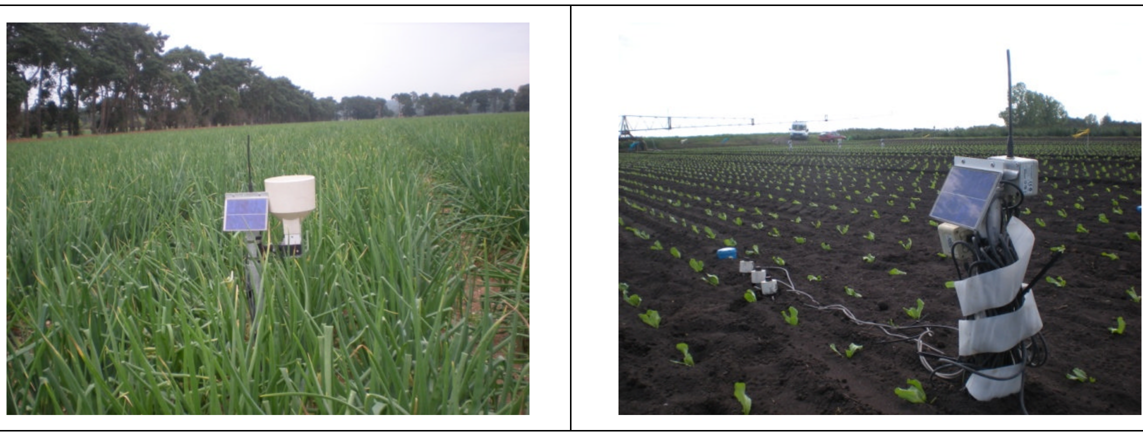
Figure 8 Tensiometers (onions) and Adcon capacitance probes (lettuces) used in the field experiments in 2011.

2.2.4.2 Wireless network

One objective of this project was to produce a network of wireless soil moisture sensors capable of monitoring in real time the changes in soil moisture content in different parts of the field. Reliable and self powered wireless technology is crucial in agriculture as it not only eliminates the burden of collecting data from the field but also eliminates the problem of wires causing delays or limiting machine trafficability in the field. The tensiometers, capacitance probes (Adcon) and raingages installed in each field were linked to short range remote telemetry units (RTU) which then transmit the soil data on a 15 minute interval (Figure 9). The RTU's (A733 addWAVE, Adcon) internal battery pack supplies the logger and radio with power, as well as the sensors and devices attached to the system. The RA440 telemetry unit (Figure 9) bridges the UHF A733 RTUs to the GPRS/GSM network. As with the A733, power comes from a standard solar panel (Figure 9). Data collected from the field is transmitted through a GSM network and then uploaded via the internet where it can be accessed by computer. This allows wireless field moisture monitoring in real time from any location.

Figure 9 Short (A733 addWAVE) and long range (RA440) remote telemetry unit and solar panels used to power the wireless soil monitoring devices in 2011.

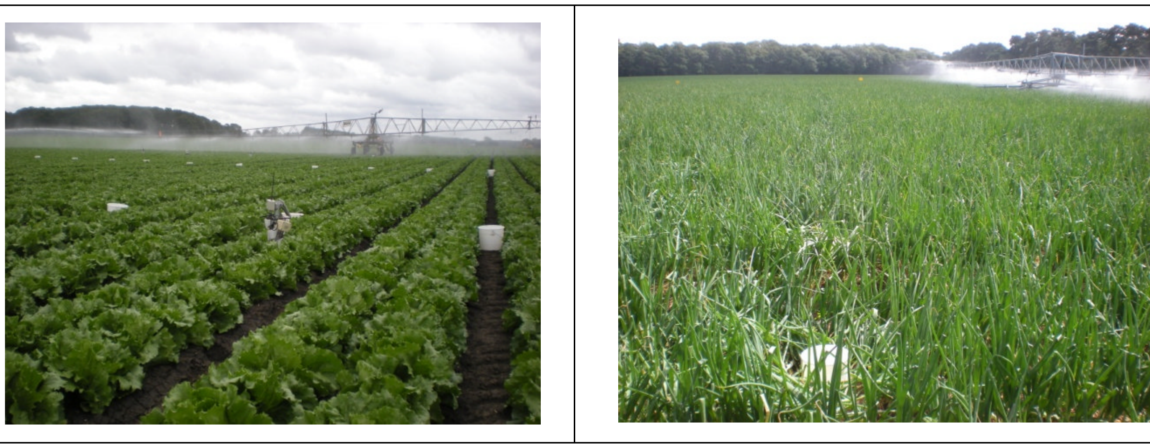
Figure 10 Wireless soil water monitoring system installed at Elveden and Ely field sites.



2.2.5 Performance assessment of the irrigation systems

In order to analyse the performance of each irrigation system at each grower site, a uniformity test was conducted on each irrigation event. At both sites (Elveden and Ely) a hosereel fitted with a boom irrigator was used for irrigation. A transect of catch cans (opening diameter 21.5cm and 30 cm height) were laid on a 1m interval across the wetted width of the irrigator. The irrigator was then allowed to pass over the sampling transect and data collected to assess the application uniformity and irrigation adequacy (Figure 11).

Figure 11 Conducting irrigation uniformity tests at Ely and Elveden field sites in 2011.



The uniformity of water application in sprinkler irrigation systems is usually reported as either the Distribution Uniformity (DU) or Christiansen's Coefficient of Uniformity (CU):

The distribution uniformity (DU) indicates the uniformity of application throughout the driest quarter of the field (Heermann et al.,1990) and is calculated by:

$$DU = 100 * \frac{Z_{lq}}{Z_{av}}$$

Where:

Zlq average of the lowest one-quarter of the measured values

Zav average infiltrated depth in the entire field

The Coefficient of Uniformity (CU), developed by Christiansen (1942):

$$CU = 100 * \left(1 - \frac{\sum |Z - m|}{\sum Z} \right)$$

Where:

Z : individual depth of catch observations from uniformity test, mm

|Z-m|: absolute deviation of the individual observations from the mean, mm

m : mean depth of observations, mm

The Distribution Uniformity (DU) is based on the lowest quartile of the irrigated area and is a good indicator of the extent of dry spots in the field. The Coefficient of Uniformity (CU) is an indicator of how equal (or unequal) the application rates are throughout the field. The average net depth of water applied at different percentage of adequately irrigated area as described by Keller and Bleisner (2000) was used to identify the percentage of the field receiving a given minimum water volume.

2.3 Results and discussion

A summary of the results relating to assessing soil variability, moisture measurement, irrigation application uniformity and crop yield are summarised below.

2.3.1 Soil variability

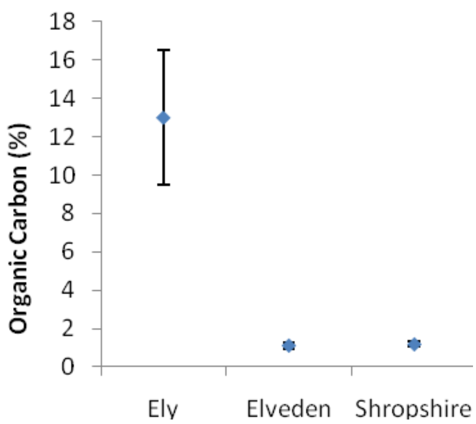
2.3.1.1 Laboratory soil analysis

The 35 soil samples collected from each field were analysed in the laboratory for organic carbon content and texture. Figure 12a shows the average value of organic carbon content obtained (the error bars reflect the variability between the sample values). Figure 12b shows the percentage of soil samples within each soil class according to the USDA texture triangle.

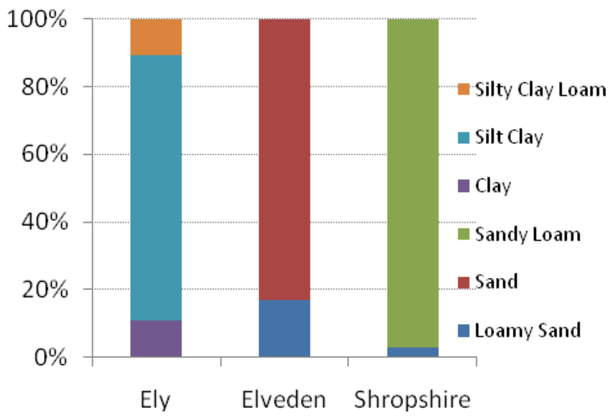
The field at Ely (compared to the Elveden and Shropshire field sites) is characterized by a large organic carbon content (~13%). The dominant soil type at Ely is silty clay whilst at Elveden sand dominates in large part of the field. At Shropshire of the 35 samples analysed, 34 were sandy loam and the other a loamy sand. Based on these analyses, the largest soil variability in terms of texture and organic carbon content was observed at Ely; the Shropshire field appears to be largely uniform and dominated by a sandy loam soil.

Figure 12 Organic carbon content (a) and percentage of soil samples in each textural class (b) at each farm site. Error bars represent range of variation between soil samples.

(a)



(b)

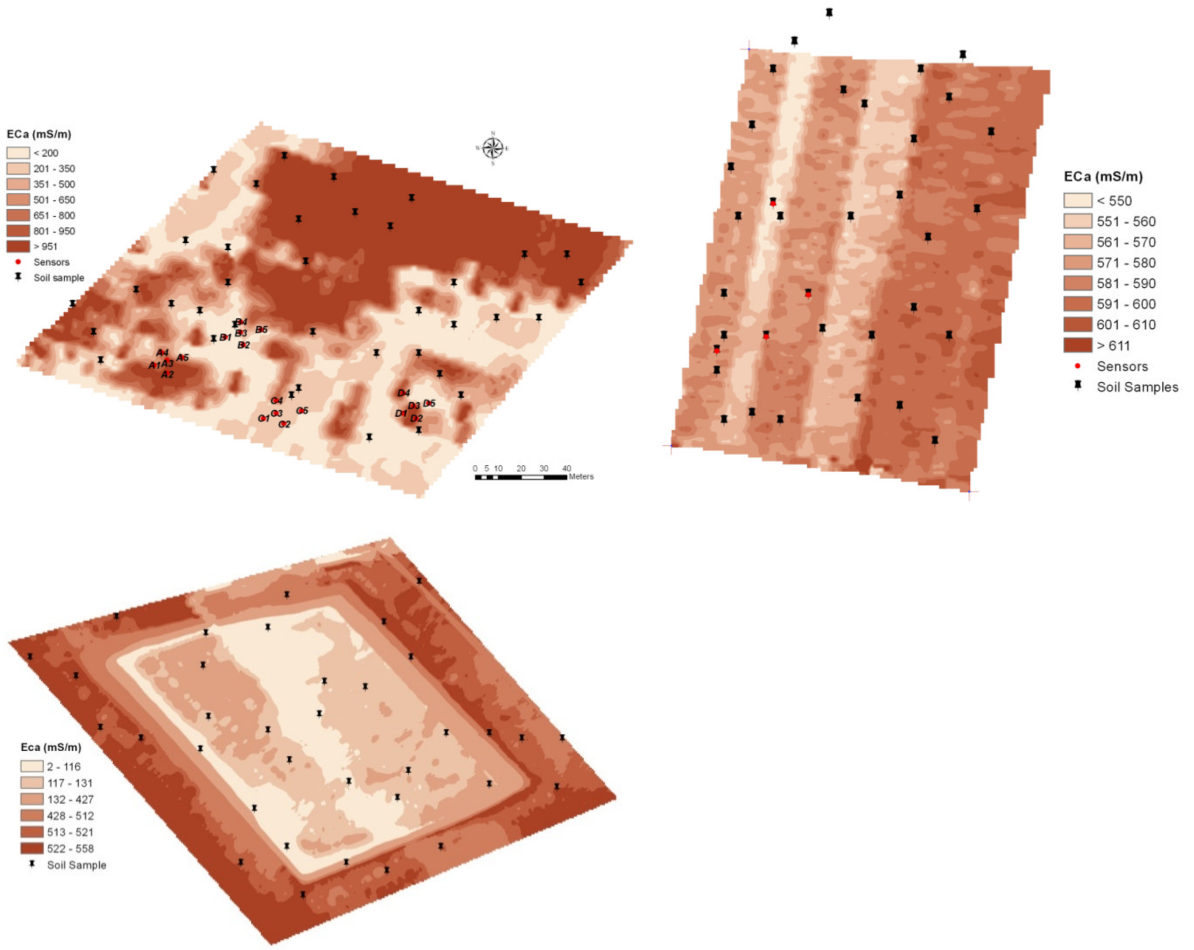


2.3.1.2 EMI soil scanning

Maps showing the spatial variation in apparent electrical conductivity (ECa) at the Ely, Elveden and Shropshire fields were produced by interpolating the measured values using a GIS krigging technique (Figure 13). The largest variability in ECa has been observed at Ely, followed by Shropshire; the field at Elveden appears to be relatively uniform. From a textural and organic content point of view this is consistent with the soil samples analysed in the laboratory (Figure 13).

At Ely, the presence of bands of alluvium soils, resulting from ancient watercourses crossing the field is a common characteristic. These are known locally as “roddens” or “silt hills” and can be easily identified from ECa maps and aerial photo (Figure 1). The presence of “roddens” was an additional cause for the high soil variability observed at the Ely site. The Elveden site is predominantly a large sandy field with low organic content and hence the observed changes in ECa values were much lower than the heavier, high carbon content field at Ely. Soil ridging in the field at Elveden has also created a fine tilth in the top soil and consequently soil variation, although minor, follows the vertical orientation of the onion beds (Figure 13). At Shropshire, the ECa values showed a correlation with land topography with lower values at the top and relatively high values on the low land probably caused by soil erosion and sediment deposition. Soil moisture sensors were installed in the Ely and Elveden fields based on the ECa maps to reflect different areas of soil heterogeneity. A description of the equipment installed at each site is given in Section 2.2.4.1 and 2.2.4.2.

Figure 13 Spatial variation of apparent electrical conductivity (ECa) measured using the EMI scanner at (a) Ely (b) Elveden and (c) Shropshire field sites.



2.3.1.3 Vis NIR soil scanning

Visual investigation of the on-line vis-NIR spectra collected from Ely (Figure 14) shows a typical soil with low reflectance (<30%). Clear absorption bands for moisture content can be observed at 1450 nm and 1950 nm, that are associated with the second and first overtones of water absorption in the NIR region (Mouazen et al., 2006; Stenberg, 2010). The low reflectance at the visible range (400 to 700 nm) is attributed to the dark soil colour associated with wavelength of blue at 450 nm (Mouazen et al., 2007). The carbon absorption band of carbon are in the NIR range and cannot be detected visually, but the multivariate PLS regression analysis is used to quantify this property in this study. A PLS (Partial Least Squares) regression model was developed based on the lab measurements and spectral analysis of soil samples collected from different fields across Europe and from those collected from these three field sites in order to create a model for soil organic carbon and moisture content prediction (Kuang and Mouazen, 2011b). The coefficient of determination (R^2), Root-Mean-Square Error of Prediction (RMSEP) and Regression Point Displacement (RPD) were used to validate the modelled outputs (Table 1).

The model shows a high prediction performance, with relatively better prediction for moisture content than organic carbon. The on-line prediction values were then compared against the laboratory organic carbon (OC) and moisture content (MC) measurements using the independent soil validation dataset. The correlation between predicted OC and MC and laboratory measured values is given in Figure 15. A coefficient of determination (R^2) of between 0.7 and 0.8 is considered acceptable for model validation. The analyses show a good level of model prediction for moisture content and an acceptable prediction for organic carbon at the Ely and Shropshire sites. At Elveden, the prediction for organic carbon was very low (R^2 = 0.24). This is mainly due to the fact that the on-line scanning was carried out on a ridged field which made the system quite unstable causing poor contact between the sensor and soil, leading to inaccuracy in the field measurements.

Figure 14 On-line reflectance spectra observed for the field site at Ely.

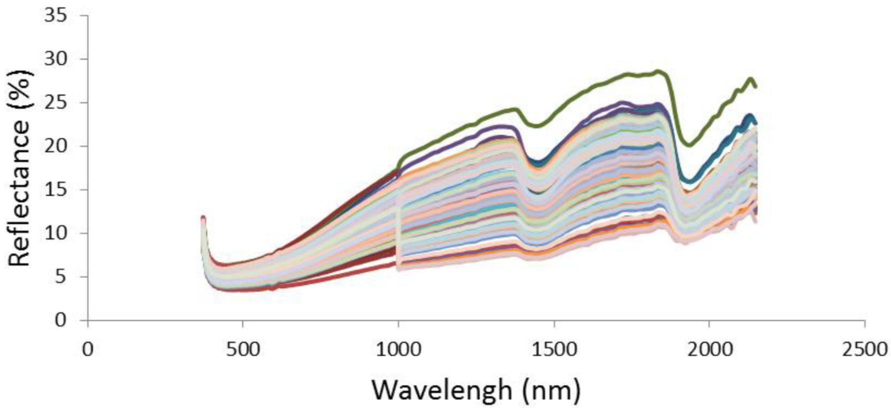


Table 1 Summary model validation results for organic carbon (OC) and moisture content (MC).

	R^2	RMSEP (%)	RPD
Organic Carbon (OC)	0.8	0.12	2.68
Moisture content (MC)	0.93	1.32	3.89

However, the difficult operating conditions experienced at Elveden have not affected the moisture content measurement, due to the clear water absorption band in the NIR range (between 1450 and 1950 nm) (Figure 14). Figure 16 and Figure 17 show the soil moisture content and the organic carbon maps of the three fields used in this study as generated by the Vis-NIR spectrometry.

Figure 15 Model predicted and observed values for organic carbon (OC) and moisture content (MC) at (a) Ely (b) Elveden and (c) Shropshire field sites in 2011.

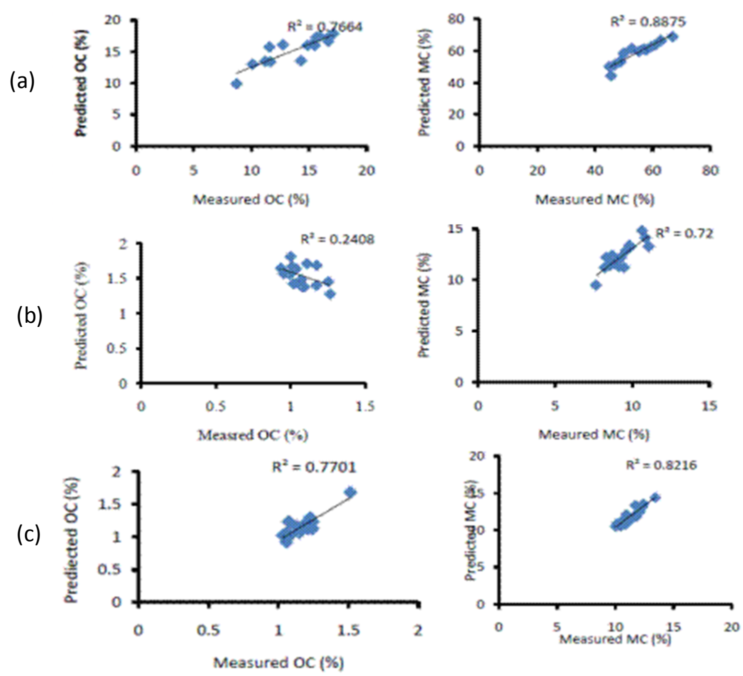


Figure 16 Derived soil moisture content maps using the online vis-NIR sensor at Ely, Elveden and Shropshire field sites.

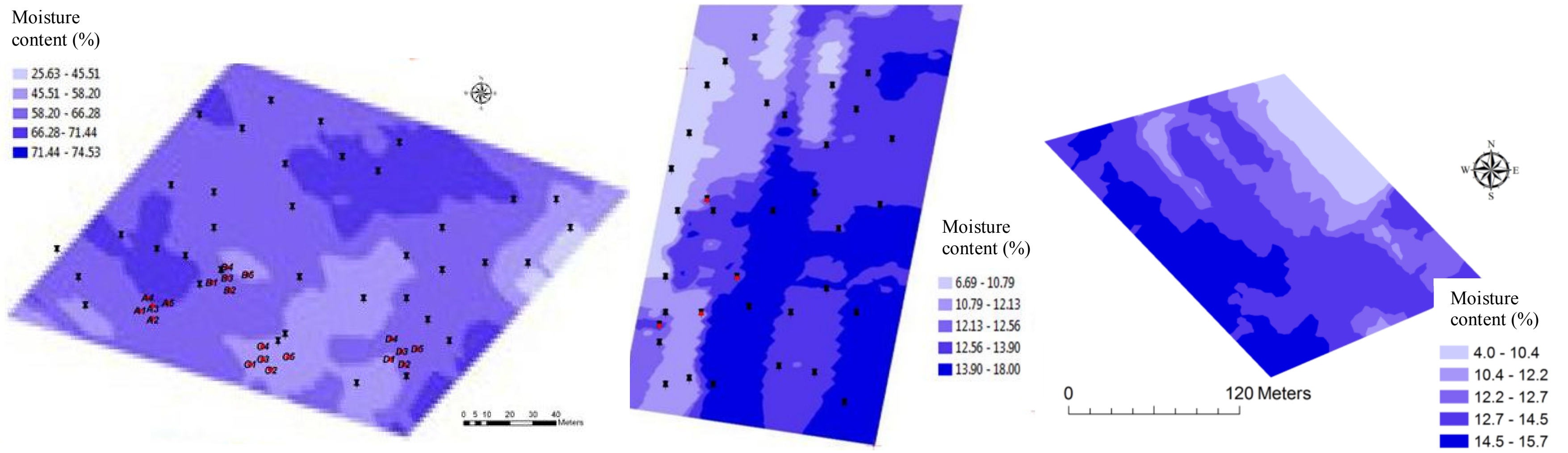
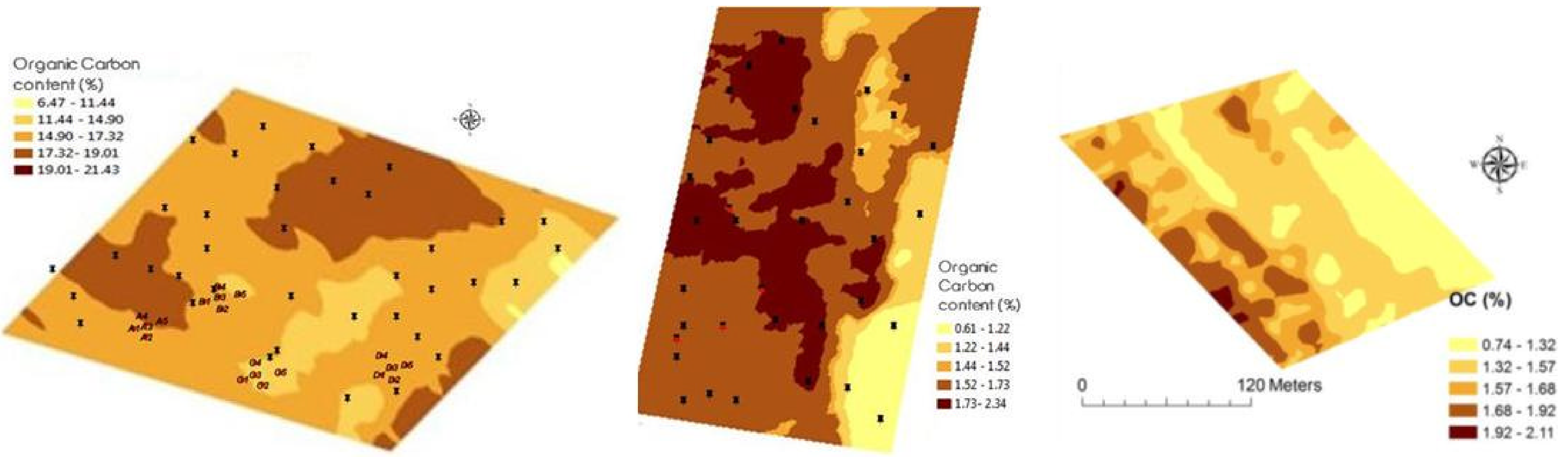


Figure 17 Derived organic carbon content (%) maps using the online vis-NIR sensor at Ely, Elveden and Shropshire field sites.



2.3.2 Soil moisture sensors

2.3.2.1 Ely field assessment

The measured soil moisture values from the capacitance probe (at 10, 20 and 30 cm depth) were averaged and summarised in Figure 18. A few problems occurred in the Ely field experiment which caused a temporarily failure in some sensors. Sensor C1 was not working for technical reasons and was replaced on 15th July. The batteries in the RTU powering sensors C3, C4 and tensiometers (even though rechargeable by solar power) were replaced 1st July. Sensor A1 was physically damaged by a tractor working in the field on 23rd June but the replacement made on 8th July. Pests (rodents) and animals biting the wires were an additional problem which caused some malfunctioning of the sensors.

However, based on the field data and sensor readings, greater variations in readings were observed between sensors in the same block (A,B,C or D) compared to sensors in different blocks (Figure 18). All the sensors have shown a clear response to irrigation applications and/or rainfall. The probes in Block B measured a low variation in water content from planting to harvesting. In contrast, the soil water content in Blocks C and D have declined steadily towards the end of the growing season as a result of the combined effect of plant water uptake and reduced frequency of water application.

Figure 19 shows the matric potential (Kpa) measured by the three tensiometers in each block and at different soil depths (15, 30 and 45 cm). The soil at Ely is a heavy clay and has a tendency to crack when it dries; hence the ceramic cup of the tensiometer can lose contact with the soil. Under these conditions, the tensiometer might give a biased reading as water is easily lost from the tensiometer tube.

Figure 18 Capacitance probe (averaged over 10, 20 and 30 cm depths) and rain gauge measurements from four different blocks (A, B, C and D) at the Ely field site.

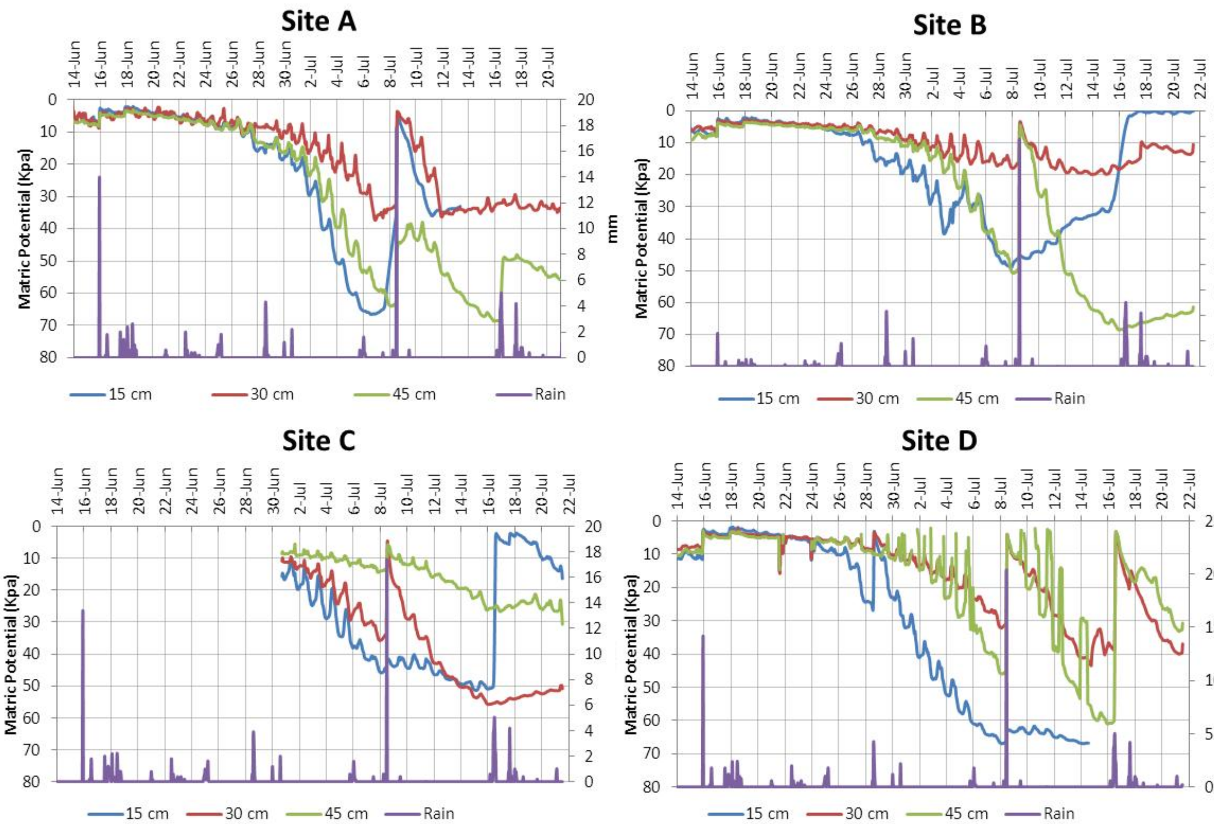
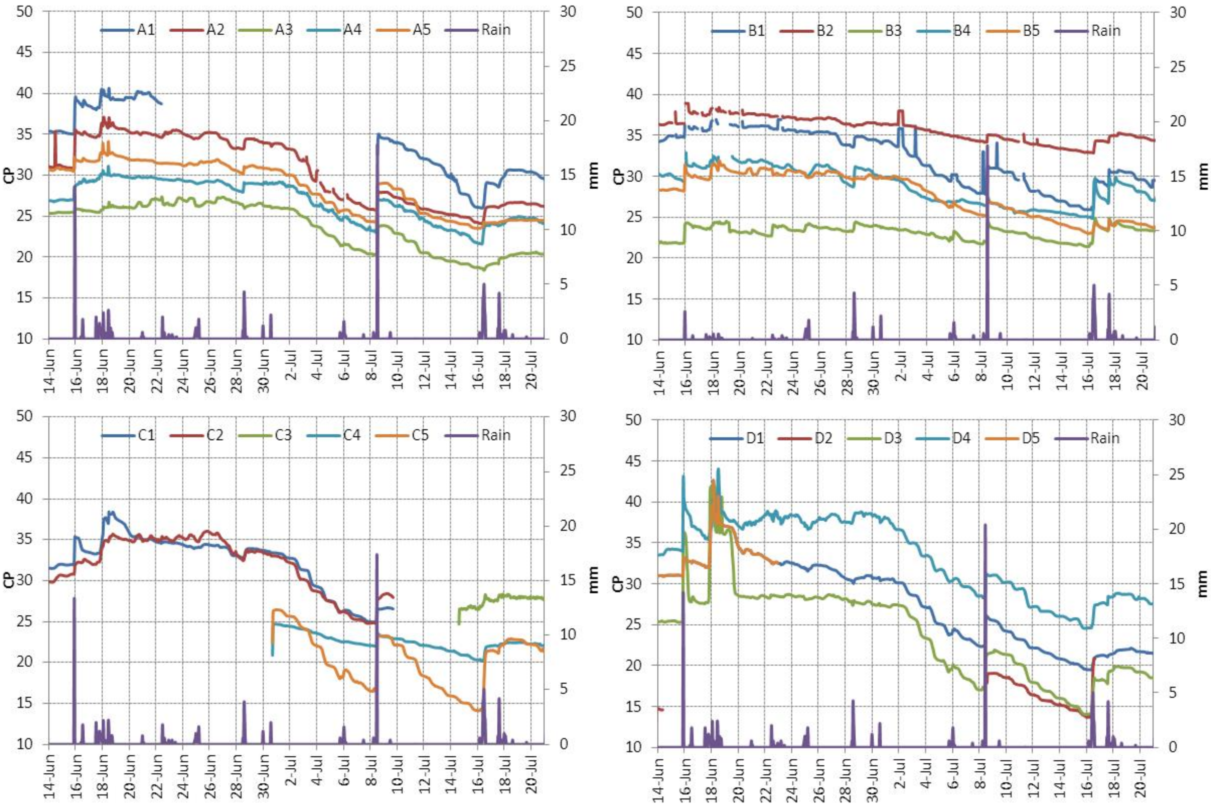


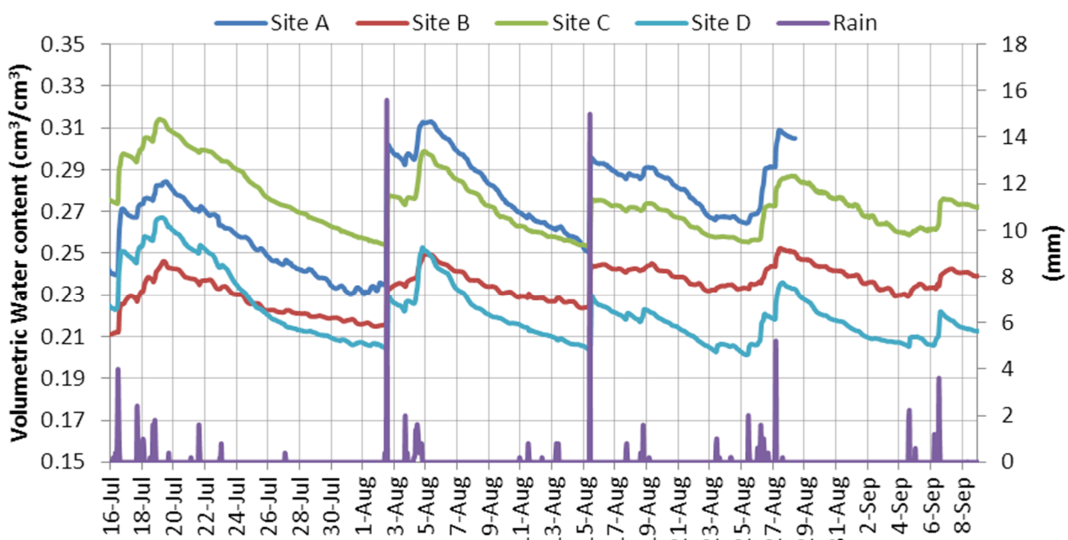
Figure 19 Matric potential measured using 3 tensiometers (at different depths 15, 30 and 45 cm) in each block (A, B, C, and D) at the Ely field site.



2.3.2.2 Elveden field assessment

The dielectrical permittivity measured by the soil moisture sensors depends on soil type. For that reason the dielectrical permittivity was transformed into volumetric water content using an empirical model described by Wang and Schmugge (1980) which takes into consideration the dielectrical permittivity of the soil composition and its texture.

Figure 20 Capacitance probe volumetric water content (averaged 10, 20 and 30 cm) and rain gauge measurements at Elveden field site. The second y-axis represents water applied (mm) by irrigation and/or rainfall.



In contrast to the other sensors, those in Block B showed a moderate response to soil wetting and drying as it maintained a relatively constant low water content throughout the season (Figure 20). The other sensors have all shown a similar trend in response to water application from either rain or irrigation during the season (Figure 20). A low soil water content measurement could be an indicator of (i) low water volume applied (non uniform rain/irrigation), (ii) poor soil water holding capacity (depending on soil texture and structure) or (iii) higher root uptake activity caused by a full canopy cover and/or extensive rooting. This is generally observed late in the growing season where the plant is fully developed and water uptake at its maximum. Taking into account these factors, the moisture probe measurements and their differences must therefore be interpreted with caution.

Relative Water Supply (RWS) is an indicator that has been used to undestand and interpret the probe readings and allow a better comparison between the 4 sets of probes. The indicator was calculated based on the following:

$$RWS = \frac{d_i - d_{\min}}{d_{\max} - d_{\min}}$$

Where:

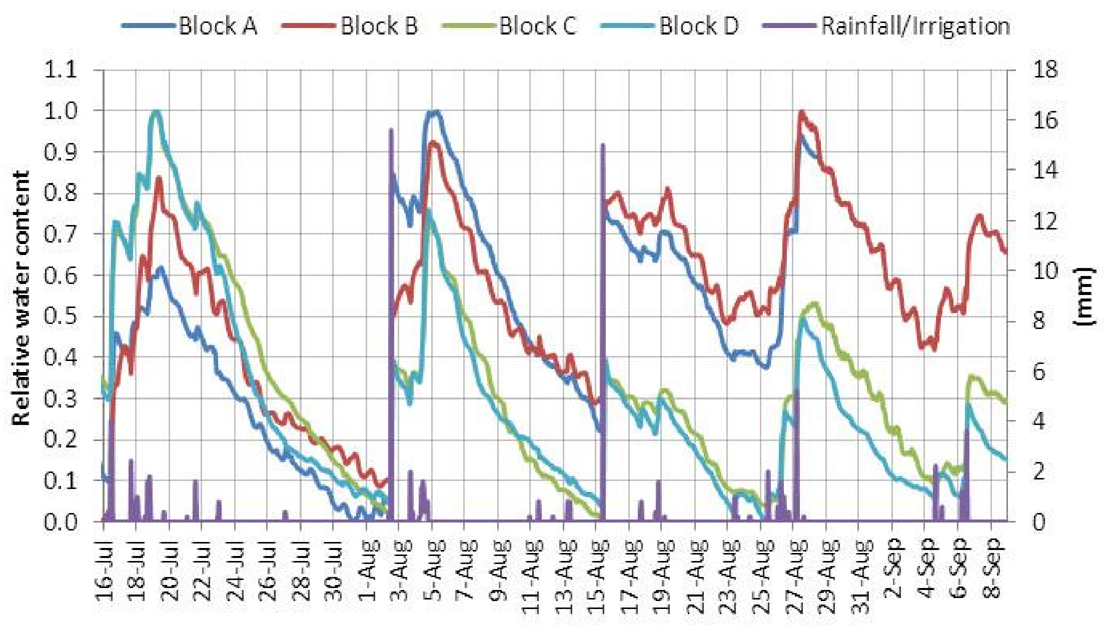
d_i is the measured dielectric permittivity

d_{min} minimum is the measured minimum dielectric permittivity

d_{max} maximum is the measured maximum dielectric permittivity

Using this indicator, the probe in Block A had a similar pattern to that in Block B, and the probe in Block C was similar to that in Block D (Figure 21). The soils in Block A and B were classified according to the laboratory analysis as sandy loam and sandy for Blocks C and D. These differences in texture might help explainthese similarity and differences in wetting and drying patterns between the blocks.

Figure 21 Relative soil water content measured using 4 moisture probes at Elveden farm site.



2.3.3 Irrigation uniformity

The uniformity of water application on the lettuces at Ely was assessed in July 20111. Two sets of catch can transect data were collected. Figure 22 summarises the data and shows the average variation in irrigation depth (mm) along the boom and observed variation between the two tests. The uniformity test was carried under relatively windy conditions. However, a high uniformity of water application was observed with both the CU and DU values of 87% and 83%, respectively. The average depth of water applied was 21 mm against a scheduled depth of 20 mm, giving an irrigation adequacy of 105%.

Figure 22 Uniformity of water application under the boom system on lettuces at Ely in 2011. Error bars represent the range of variation between two uniformity test measurements.

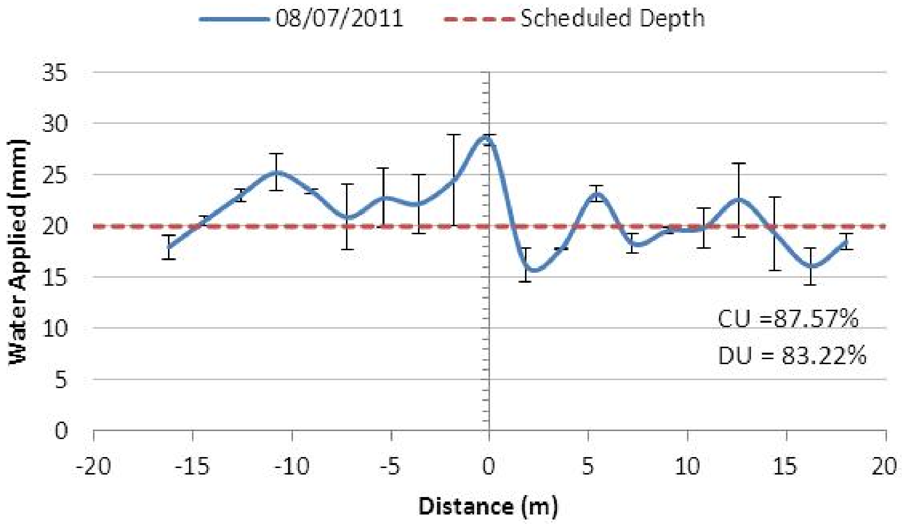
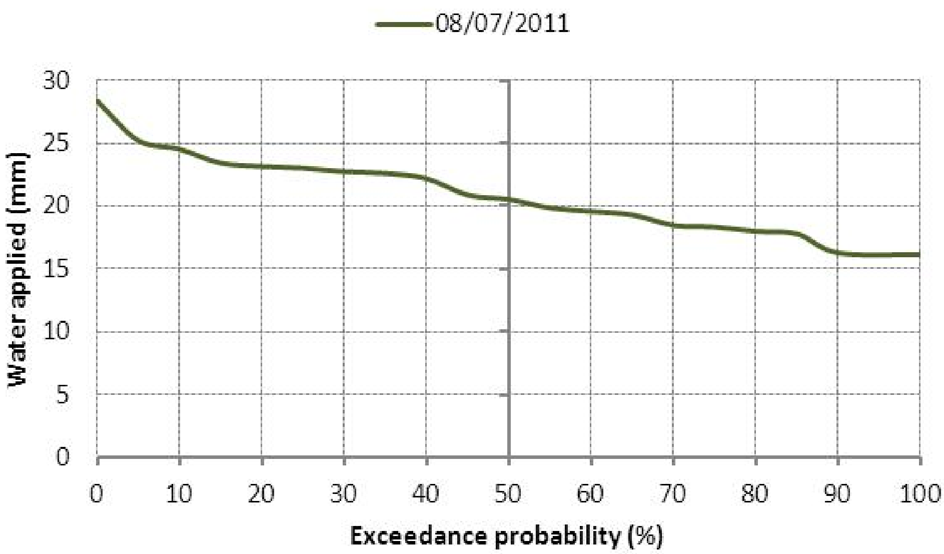


Figure 23 shows that the average (50% probability of exccedance) depth of water applied by the boom is 20mm whilst the driest (10% probability) and wettest areas (90% probability) actually received <16mm and >25 mm, respectively.

Figure 23 Probability of exceedance for the depth of irrigation water applied by the hosereel and boom system on lettuces at the Ely field site, based on data for 2011.



At Elveden, two uniformity tests were conducted on 2nd and 15th August 2011. The equivalent water distribution pattern of the irrigation system is shown in Figure 24. The CU on the first and second irrigation were very similar (81 and 82%). The DU was much lower during the first irrigation (65%) compared to a DU of 74% on the second irrigation.

The average water application (Figure 25) was calculated to be 16.5 mm and 15 mm for the first and second irrigations, respectively. The average depth of water applied was 15.75 mm against a scheduled depth of 15 mm, giving an irrigation adequacy of 105%.

The wettest areas (10% exceedance) of the field received 19mm and 17 mm (first and second irrigation events), whilst the driest areas (90% exceedance) received <10 mm on both irrigation events (Figure 25).

Figure 24 Uniformity of water application on 2nd and 15th August 2011 at the Elveden field site.

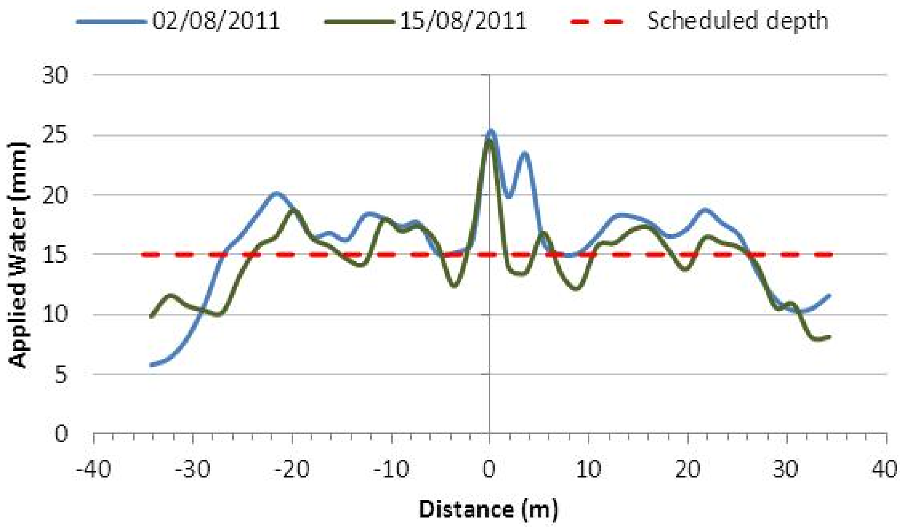
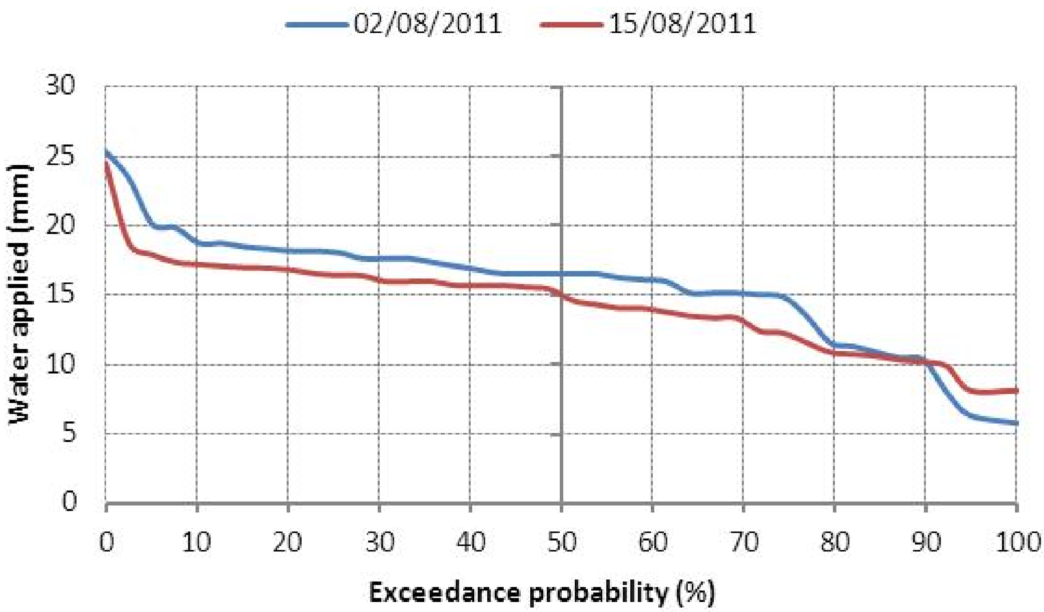


Figure 25 Probability of exceedance for the depth of irrigation water applied by the hosereel and boom system on onions at the Elveden field site, based on data for 2011.

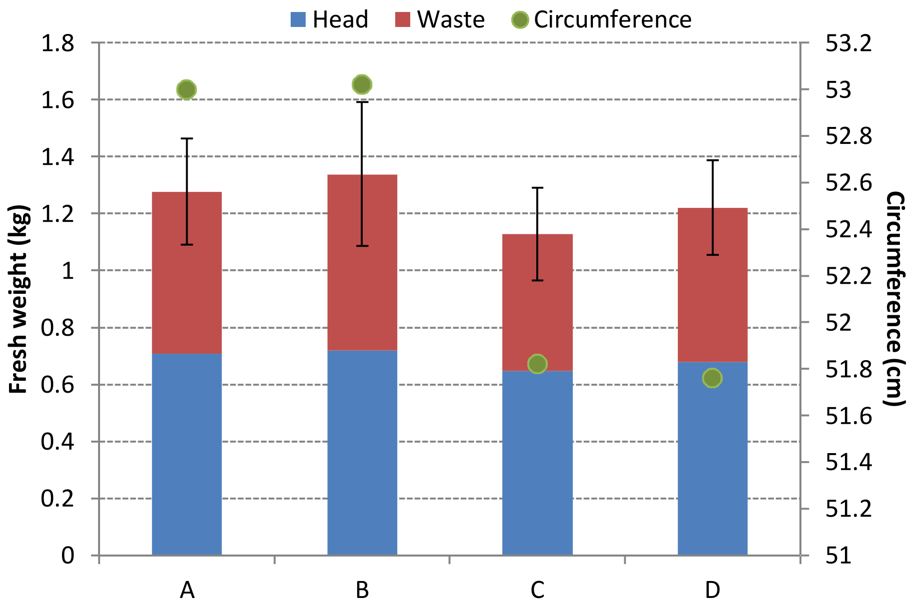


2.3.4 Observed variability in crop yield

2.3.4.1 Lettuces at G's

From each block where soil moisture sensors were installed, 50 lettuces were cut and weighed in the laboratory at Harper Adams for total fresh, head and waste weight (Figure 26). The average circumference of the plants within each block was also measured (Figure 26). A summary of the mean fresh and dry weights for lettuces harvested from each of the four blocks at G's in 2011 is summarised in Table 2.

Figure 26 Measured mean fresh and dry weight (g/head) of lettuce heads harvested in each block at Ely field site in 2011.



For fresh weight, the lettuce heads in Block C were significantly lighter than all the others and the least significant difference (LSD) between any of the means at a 5% probability level (5% LSD) was 76g. For the head fresh weight a statistically significant difference was observed between Block C, and Blocks A and B with a 5% LSD of 43.5 g per head. No significant difference was observed between Block A and Block B for fresh weights or for the head circumference. Head weight, waste weight and head circumference between block C and Block D were also not significantly different. A summary of the statistical analysis is presented in Table 2.

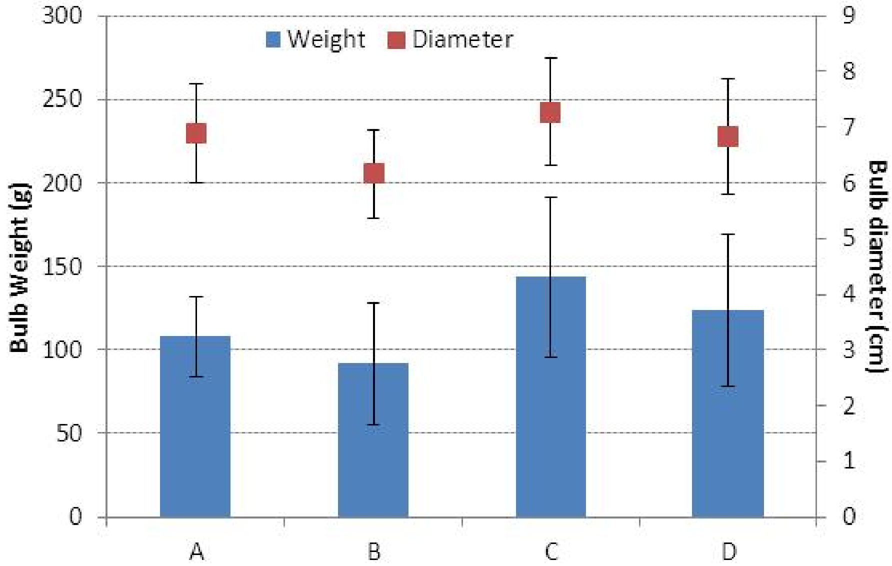
Table 2 Yield variation for lettuce (circumference, total, head and waste fresh weight) between blocks (A to D) for Ely field site in 2011.

Variate	**A**	**B**	**C**	**D**	**LSD(5%)**	**p=**
Circumference (cm)	53	53.02	51.82	51.76	1.096	0.024
Total FW (Kg)	1.277	1.339	1.128	1.22	0.0763	<.001
Head FW (kg)	0.7092	0.72	0.6484	0.6804	0.04353	0.006
Waste FW (Kg)	0.568	0.619	0.48	0.54	0.0604	<.001

2.3.4.2 Onions at Elveden

Using a similar methodological approach, a random sample of onions were harvested from each block in the onion field at Elveden and their fresh weights and diameter determined (Figure 27).

Figure 27 Measured bulb fresh weight (g/bulb) and diameter (cm) of onions harvested in each block at Elveden Estate (Suffolk).



The data showed a significant difference between Blocks B and C for fresh weight. The least significant difference (LSD) between the means at a 5% probability level (5% LSD) was 38 g for fresh weight. No significant difference in fresh weight has been observed between Blocks A, C and D.

3 Polytunnel experiments

Three experiments were completed at HAUC using glasshouse and polytunnel facilities to study the effect of soil moisture variability on:

1. Onion growth, crop water status and depth of water accumulation (HortOnion01);
2. Lettuce growth, crop water status and depth of water accumulation (HortLet02), and;
3. Lettuce rooting depth and distribution (HortRhizo01).

The key findings are summarised below.

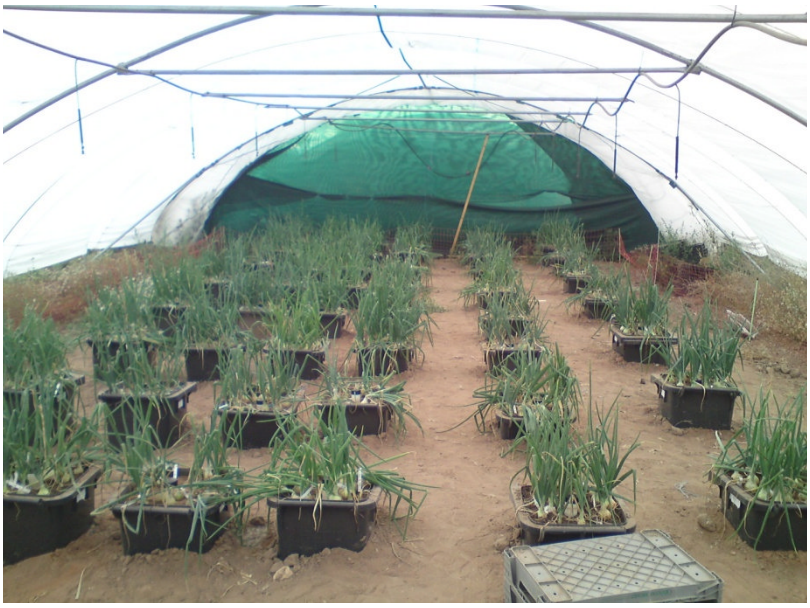
3.1 Onions (HortOnion01)

3.1.1 Materials and methods

An onion crop was grown in two defined soils in a polytunnel which protected the crop from rainfall. Wheelie bins with holes drilled in their bases for drainage were buried to a depth of 50 cm leaving approximately 30 cm above the soil surface. The bins had a stepped base giving average height of 76.45 cm with a surface area of 40 cm × 44.5 cm = 1780 cm^2. The total bin capacity was 136 l.

Soil taken from the location of the polytunnel (Table 3) 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 (Figure 28). Nitram (160 kgN ha^{-1}) was added to the bins at the start of the trial. Twenty onion seeds (*cv Arthur*) were sown on 15 April 2011 and thinned to 15 plants (84 m^{-2} compared to an industry standard of 50 m^{-2}).

Figure 28 Hortonion01 – experimental site under the polytunnel at HAUC (Summer 2011).



Soil moisture content was measured using a Diviner probe every week and initially water was added to maintain the soil close to field capacity (FC). Water was applied weekly using a watering can with a measured volume of water for each bin. Irrigation treatments were imposed from 29 June 2011 (Day 0) when onions had an average of 6 leaves. There was no difference between treatments in the number of plants per bin or average leaf number per plant at the start of the trial. Five plants were tagged in each bin for identification.

During imposition of treatments total soil moisture was measured in each bin on Wednesday morning and calculated volumes of irrigation water were applied Wednesday afternoon. Soil moisture was again measured on Thursday morning. Irrigation treatments imposed a wide range of stress effects based on the available water capacity (AWC) of the soils. The AWC was calculated from both pressure membrane data (0.05 to 5 bar) and calibration curves established from supplementary tubs by flooding and then moisture measurement over a 7 day period. The dry treatment received no water after irrigation treatments started.

Irrigation volumes were calculated to return the very wet bins to 90% FC and the wet and moderate treatments received 66 and 33% of this volume until bins reached a target value of 90, 63, 35 and 8% of AWC. These treatments added progressive stress to the plants as all of the tubs were maintained close to field capacity until the imposition of the irrigation treatments. The 90% treatment was chosen over a 100% treatment to ensure that soils were never saturated.

Plants were lifted from the soil on 2 September 2011 (Day 65) and left to 'field cure' on top of the bins for 4 days before being placed in a drying oven (6 September 2011) for 7 days at 30°C, followed by bin drying with ambient air for 21 days.

Table 3 Unamended polytunnel soil properties used for the experimental fieldwork in 2011.

Organic Matter	2.26%
Texture	Sandy loam
pH	6.4
P	68 (mg/l)
K	142 (mg/l)
Mg	71 (mg/l)
Ammonium–N (0-90 cm)	7.22 (mg/kgDM)
Nitrate-N (0-90 cm)	10 (mg/kgDM)
Total N (0-90 cm)	0.38 (g/100gDM)
SMN (0-90 cm)	68.88 (kg/ha)

3.1.1.1 Experimental design

The wheelie bins were set into the soil in six blocks, with each of the eight treatments randomly placed within the block (Table 4).

Table 4 Experimental design and layout for 2011 polytunnel fieldwork.

Soil type	Irrigation	Treatment
Low OM	Dry	1
Low OM	Mod	2
Low OM	Wet	3
Low OM	Very wet	4
High OM	Dry	5
High OM	Mod	6
High OM	Wet	7
High OM	Very wet	8

Block 1	5	8	6	7	4	1	3	2
Block 2	7	5	3	4	1	6	2	8
Block 3	2	5	8	3	6	4	7	1
Block 4	8	1	4	7	2	5	6	3
Block 5	6	7	1	2	8	3	4	5
Block 6	1	4	3	7	2	6	5	8

3.1.1.2 Assessments

Soil moisture was measured using the Diviner™ probe at 10 cm intervals (10 to 80 cm) in each bin before and after irrigation each week (as described above).

Crop growth The length of the youngest fully expanded leaf and leaf number were assessed using 5 tagged plants per bin weekly.

Crop water status These measures were taken between 9.30 and 11.00 using untagged plants from Blocks 1, 3 and 5 of all treatments in the high OM soil. Leaf temperature was assessed using an IR thermometer with one reading per youngest fully expanded leaf taken from two plants per bin. Wet and dry filter papers were used as fixed constants and values were taken for these with each leaf assessed. Stomatal conductance (APSII meter) was measured with one reading in the centre of the youngest fully expanded leaf of two plants per bin. Relative water content (RWC) was assessed destructively from a central 10 cm section cut from one fully expanded leaf of three plants per bin. The leaf section was weighed fresh, rehydrated for 4 hours in distilled water at 4°C and weighed turgid. Finally the leaves were dried at 80°C for 48 hours and weighed dry. RWC in the fresh leaf was calculated as a proportion of the range between dry weight and turgid weight.

Harvest assessments At harvest the total weight of trimmed bulbs (Y_{wet}) was measured for each bin, prior to curing. The foliage was bulked for each bin and dried in an oven at 80°C for 3 days before weighing (Y_{dry}). The five tagged bulbs and one additional bulb were weighed and the circumference around the equator of each bulb measured for bulb size. The average bulb fresh weight and size was then derived for the tagged bulbs.

Irrigation water use efficiency (IWUE) was calculated as:

$$IWUE = \frac{Y_{wet} - Y_{dry}}{Water\ applied\ after\ treatments}$$

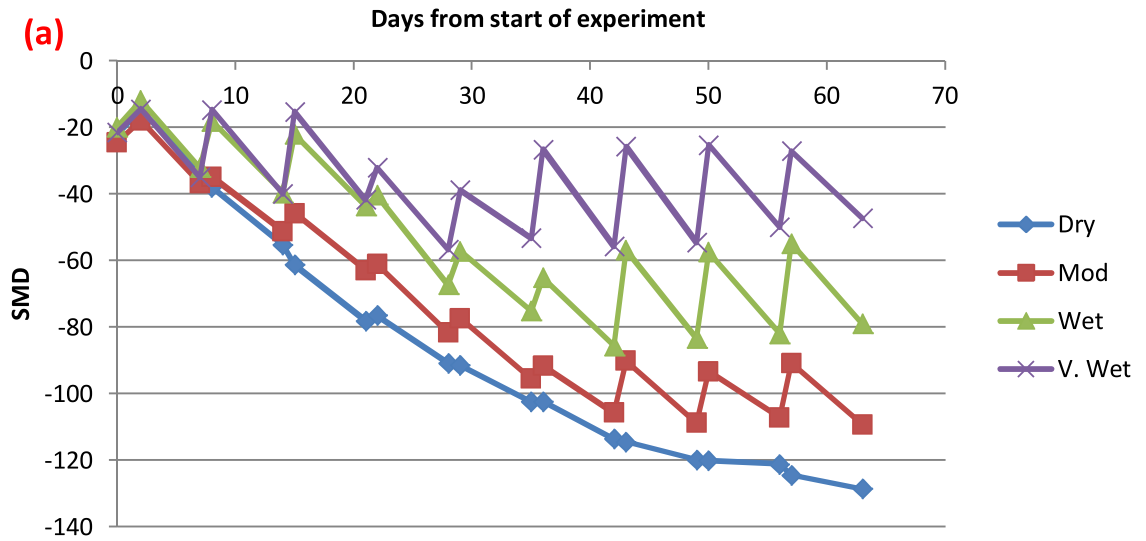
Statistical analysis Data were analysed using one-way and two-way ANOVA (Genstat 13th Edition).

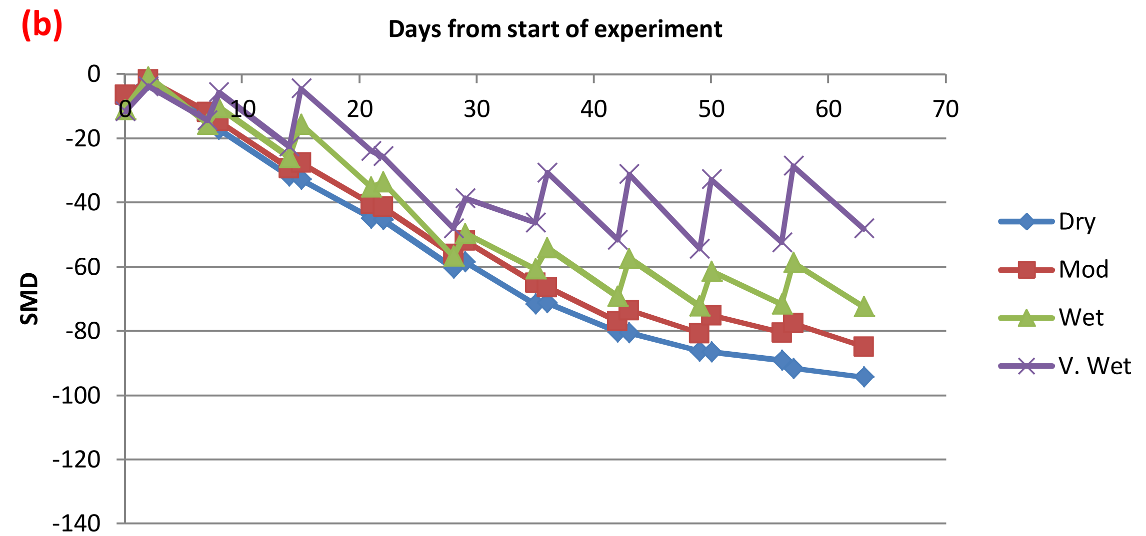
3.1.2 Results: soil moisture variation

3.1.2.1 Soil Moisture Deficit (SMD)

A range of soil moisture deficits (SMD) were generated in both the high and low OM soils (Figure 29). By the end of the experiment, the dry treatment had reached a SMD of 129 mm in the high OM soil and 94 mm in the low OM soil. The maximum values in both soils declined by approximately 10 mm and 20 mm in the high and low OM soils respectively in the first 4-5 weeks of treatments suggesting that the soil was still settling in the bins and reducing the water holding capacity of the soils. Overall, the spread of treatments was wider in the high OM soil as a result of its relatively higher water holding capacity.

Figure 29 SMD during experiment a) high organic matter soil; b) low organic matter soil.





3.1.2.2 Water loss/use

Accumulated weekly water loss

The accumulated weekly loss of water from the bins was similar for the dry treatment in both soils but was relatively greater for the irrigated treatments in the high OM soil (Table 5).

Table 5 Accumulated loss of water (mm) from the wheelie bins during experiment.

	High OM	Low OM
Dry	100	86.2
Mod	156	95.7
Wet	204	138
Very Wet	214	160

Weekly water use by depth

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. Both soils showed similar responses but, overall, the high OM soil showed a wider range of response. No differences between treatments were apparent in the first week of treatments (days 2-7). By the following week (days 8-14) the change in water content at 10 cm accounted for the largest proportion of total water use in the irrigated treatments for both soils. In contrast, the largest proportion of total water use in the dry treatment was at 30 cm for the high OM soil and 20 cm for the low OM soil. This trend continued the following week (days 15-21) with peak water use for the dry treatment moving deeper to 40 cm in both soils.

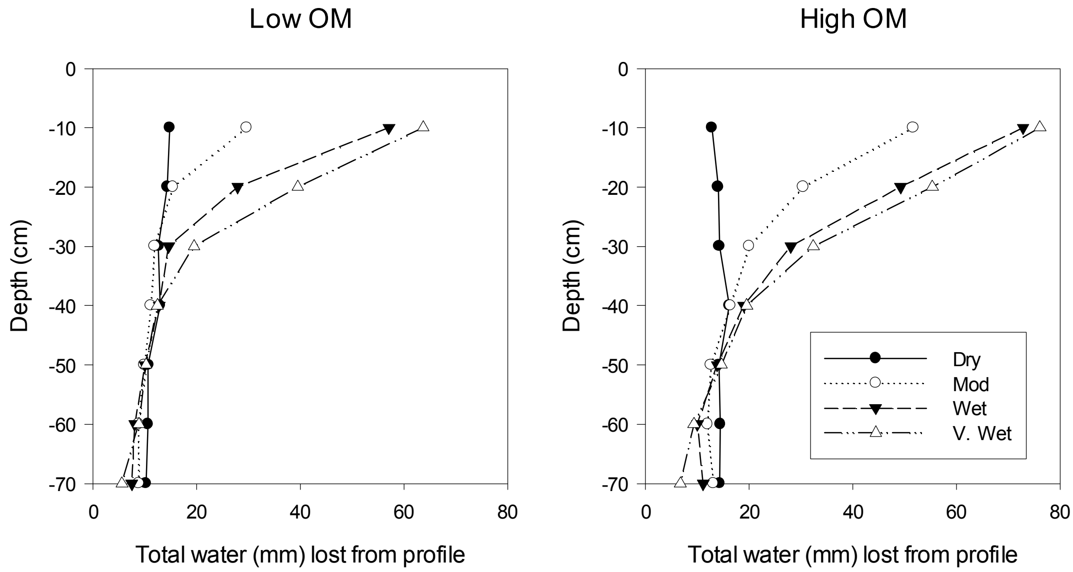
Water use differed in pattern for the two soils between days 22 and 28 with all treatments in the low OM soil using the greatest proportion of water between 30 and 50 cm. In the high OM soils, water use at 10 cm was related to water application with V. wet > Wet > Moderate > Dry, but from 40 cm the pattern was inverted with water use Dry > Moderate > Wet > V.wet. This pattern was observed in the high OM soil for 3 weeks. The differences between treatments were less clear in the low OM soils over this time.

From day 29-35 until harvest the dry treatments in both soils consistently had peak water use at 70 cm. The moderate and wet treatments, and intermittently the V. wet treatments, also showed that more water was being used at depth (i.e. 60 - 70 cm) relative to the middle (i.e. 30 - 50 cm) of the bins from day 29 - 35 but by day 43 - 49 the top 30 – 40 cm accounted for substantially more water use and this pattern remained until harvest.

Total water use by depth

Water loss varied with treatment with the greatest loss from the irrigated treatments at 10 cm depth (Figure 30). 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.

Figure 30 Total water loss calculated from weekly differences in soil moisture deficit (SMD).



The experiment generated a wide range of SMD. 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. The water use in the top 30 cm was most important for the irrigated treatments but includes an unquantified proportion of evaporative loss.

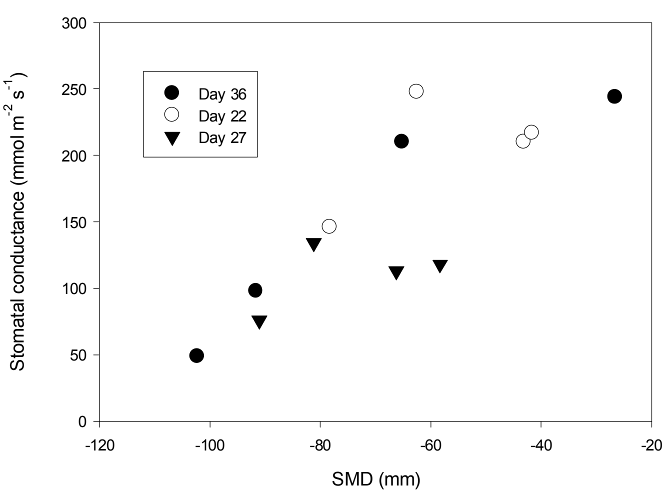
3.1.3 Results: crop water status (high OM only)

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 day 41 but irrigated treatments had less than 10% fall over.

3.1.3.1 Stomatal conductance

Stomatal conductance was measured on day 22, 27 and 36. 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 SMD. There was no correlation with SMD at days 22 or 27 or significant difference between treatments. By day 36 stomatal conductance reduced significantly with increased SMD. A polynomial line ($y = -0.045x^2 - 3.12x + 193.08$; $R^2 = 0.998$) described the response (Figure 31).

Figure 31 Relationship between stomatal conductance and SMD.



3.1.3.2 CWSI

The data from CWSI was very variable and the values for midday readings from Day 23 – 40 only were compared. Overall the dry treatments exhibited greatest stress (i.e. were warmer) than the v. wet treatments, significantly so on day 23 and 40. The moderate and wet treatments did not differ significantly on any date.

3.1.3.3 Relative water content

The relative water content (RWC) of leaves declined generally over time for all treatments. Although the dry treatment had the lowest relative water content from the end of the second week of treatments (day 14), this difference was not significant.

Crop water status measures based around stomatal function were variable and influenced by time of day and conditions at the time of measurement but showed some potential. Relative water content did not show promise.

3.1.4 Results – Crop growth

3.1.4.1 Leaf number

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

3.1.4.2 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 in both soils but the differences were not significant.

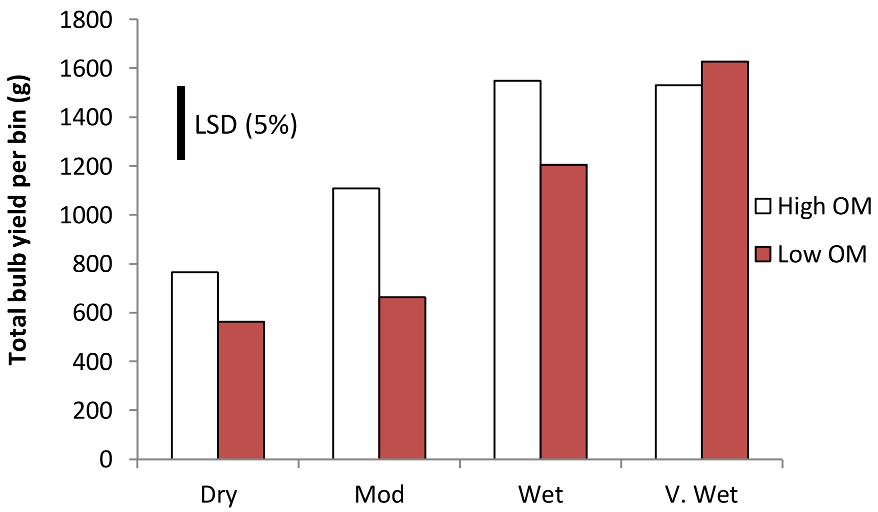
Leaf measurements did not respond to treatment and are not a good measure of soil water status.

3.1.5 Results – Harvest

3.1.5.1 Total bulb yield

Both soil OM and irrigation had a significant effect on the total yield of onions. Overall, the high OM soil produced 1239 g bin^{-1} (69.6 t ha^{-1}) significantly more than the low OM soil which produced 1015 g bin^{-1} (57.0 t ha^{-1}). Irrigation had a significant effect on the onion yield with yields increasing with irrigation (Figure 32).

Figure 32 Average bulb yield per bin (fresh weight g).



The two soils responded differently with the low OM showing no difference between the dry and moderate treatments but significant yield increase in the wet and v. wet treatments. In contrast, the yields in the high OM soils significantly increased with irrigation in the dry to wet treatments but no additional yield was achieved with additional irrigation between the wet and very wet treatments.

3.1.5.2 Total foliage DW

No significant difference was observed in the foliage biomass.

3.1.5.3 Average Yield (n=6)

As with total yield, the high OM soil had a significant main effect producing a significantly greater average yield of bulbs with 96.4 g compared to 78.8 g in the low OM soil. Irrigation increased yield significantly but there was no significant yield increase for irrigation at the wet or very wet level compared to the moderate treatment in the high OM. In contrast, there was no significant increase with the moderate treatment but both the wet and very wet treatments significantly increased yields in the low OM soil.

3.1.5.4 Average Circumference (n=6)

A similar pattern of response was observed in the average onion size. Irrigating the onions significantly increased onion size but no significant differences were observed between the irrigated treatments in the high OM soil. In the low OM soil, there was no significant increase in size with moderate irrigation compared to the dry treatment but the onion size was significantly greater with the wet treatment and similar for the v. wet treatment.

Soil OM had a significant influence on the impact of the irrigation treatments on bulb yield. Overall, bulb yield increased with irrigation treatments. However, in the high OM soil there was no increase in yield at the v. wet treatment compared to the wet treatment whereas yield significantly increased with the same treatment in the low OM soil. Bulb size responded similarly to yield.

3.1.5.5 Water Use efficiency

Irrigation WUE increased with the amount of water applied in the low OM soil but was greatest in the wet treatment in the high OM soil, declining as additional water was applied in the very wet treatment.

WUE was affected by soil organic matter. At the high OM, WUE declined at the highest irrigation level suggesting that soil water availability was not limiting in the wet treatment in this soil but was in the low OM soil.

Table 6 Total water applied and irrigation water use efficiency (IWUE) (g l^{-1}).

	Water applied (l bin^{-1})		**IWUE (g l^{-1})**	
	High OM	Low OM	High OM	Low OM
Dry	0.0	0.0	-	-
Moderate	20.1	9.4	17.0	10.6
Wet	38.5	28.1	20.4	22.9
Very wet	54.9	43.7	13.9	24.3

3.2 Lettuce (HortLet02)

3.2.1 Materials and methods

Iceberg lettuce plants (*cv Challenger*) were grown from transplants in wheelie bins in the same manner as described for the onions. Four transplants were placed in each bin on 14 July 2011 (Day 0) and, following establishment, irrigation treatments started on 20 July 2011 (Day 6). The plants were harvested on 31 August 2011 (Day 48).

During imposition of treatments total soil moisture was measured in each bin on Wednesday morning and calculated volumes of irrigation water were applied Wednesday afternoon. Soil moisture was again measured on Thursday morning. Irrigation treatments imposed a wide range of stress effects based on the available water capacity (AWC) of the soils. The AWC was calculated from both pressure membrane data (0.05 to 5 bar) and calibration curves established from supplementary tubs by flooding and then moisture measurement over a 7 day period. Irrigation treatments imposed a wide range of stress effects based on the available water capacity (AWC) of the soils. The AWC was calculated from both pressure membrane data (0.05 to 5 bar) and calibration curves established from supplementary tubs by flooding and then moisture measurement over a 7 day period. The dry treatment received no water after irrigation treatments started. Irrigation volumes were calculated to return the very wet bins to 90% FC and the wet and moderate treatments received 66 and 33% of this volume until bins reached a target value of 90, 63, 35 and 8% of AWC. These treatments added progressive stress to the plants as all of the tubs were maintained close to field capacity until the imposition of the irrigation treatments. The 90% treatment was chosen over a 100% treatment to ensure that soils were never saturated.

3.2.1.1 Experimental design

Bins were set into the soil in six blocks, with each of the eight treatments randomly placed within the block. However, it was clear that growth in some bins in block 6 was atypical and so it was removed from the experiment.

Table 7 Experimental design and layout

Soil OM	Irrigation	Treatment
Low	Dry	1
Low	Mod	2
Low	Wet	3
Low	V wet	4
High	Dry	5
High	Mod	6
High	Wet	7
High	V wet	8

Block 1	5	4	3	2	1	6	7	8
Block 2	2	1	8	6	3	5	4	7
Block 3	3	8	6	2	7	1	5	4
Block 4	6	5	7	8	4	1	3	2
Block 5	4	3	1	6	2	7	8	5

Figure 33 HortLett02 – experimental site at HAUC in Summer 2011.

3.2.1.2 Assessments

3.2.1.2.1 Soil moisture

Soil moisture was measured using the diviner probe at 10 cm intervals (10-80 cm) in each bin before and after irrigation each week (as described above).

3.2.1.2.2 Crop growth

Each week the number of fully expanded leaves on each plant was counted, until heading began, and the length of the youngest fully expanded leaf on each plant was measured.

Crop water status

Leaf temperature was assessed using an IR thermometer with one reading taken from the centre of the youngest fully expanded leaf of two plants per bin. Wet and dry filter papers were used as fixed constants and values were taken for these with each leaf assessed. Leaf temperatures were assessed at two or three times during the day and were measured on nine days during the experiment. These dates included days when the bins were irrigated (days 13, 20, 27 and 41).

Stomatal conductance measurements and relative water content (RWC) samples were taken between 9.30 and 11.00 using two plants per bin from blocks 1, 3 and 5 of all treatments in the high OM soil. Stomatal conductance (APSII meter) was measured with one reading in the centre of the youngest fully expanded leaf, avoiding large veins or the mid rib. Measurements were taken on the day before irrigation and the day after irrigation.

RWC was assessed destructively from a half leaf cut, avoiding the mid rib, from one fully expanded leaf. The leaf section was weighed fresh, rehydrated for 4 hours in distilled water in a fridge at 4°C and weighed turgid. Finally the leaves were dried at 80°C for 48 hours and weighed dry. RWC in the fresh leaf was calculated as a proportion of the range between dry weight and turgid weight. Measurements were taken on two dates, Days 29 and 43.

Harvest assessment

Plants were cut at the base and the total biomass was recorded for all four plants per bin. The waste was trimmed and both the head weight (marketable yield) and head circumference (head size) around the equator were recorded. Three heads per bin were wrapped in perforated bread bags and labelled before placing in an unlit cold store (1-5°C). The head and waste of one plant per bin was dried in an oven at 80°C for 5 days and the dry weight (Y_{dry}) recorded allowing calculation of head and waste dry matter proportion.

Irrigation water use efficiency (IWUE) was calculated as:

$$IWUE = \frac{Y_{wet} - Y_{dry}}{Water\ applied\ after\ treatments}$$

Post-harvest assessment

Post-harvest assessments were made on 1, 10 and 20 days after harvest on one head per bin. The outer was removed from the head and RWC was determined as described previously, using the second leaf. Solute leakage was determined using a method described by Wagstaff et al. (2007). The outer was removed from the head and a disc (5 cm diameter) was cut from the second leaf, avoiding large veins or the mid rib, and transferred to 500 ml beakers, which were then filled with 200 ml deionised water. This step was followed by 3 hours incubation at ambient temperature. Conductivity was measured in microSiemens (µS) using a JENWAY model 4510 conductivity meter. Samples were removed from solution and slowly frozen at −24 °C to ensure maximum disruption of membranes prior to re-measuring the conductivity using the same method as for fresh tissue. Leakage was then expressed as % of maximum conductivity for each sample.

Quality assessment was scored using 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 mis-shapen head.

Statistical analysis

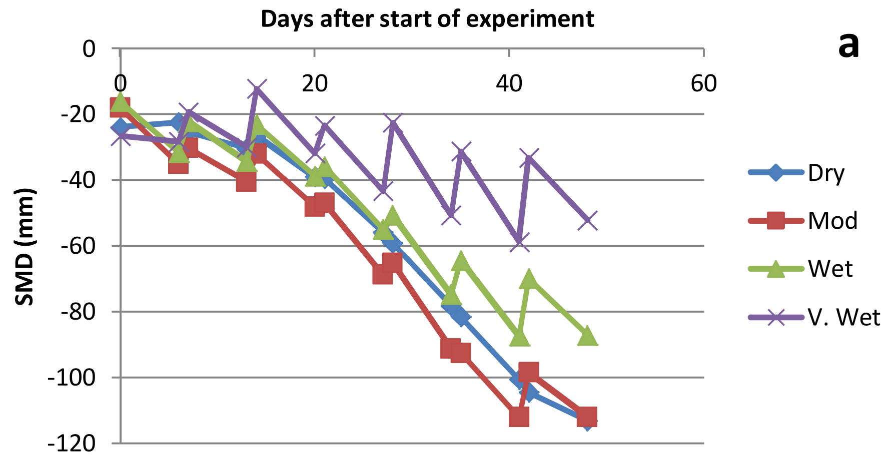
Data were analysed using one-way and two-way ANOVA (Genstat 13th Edition).

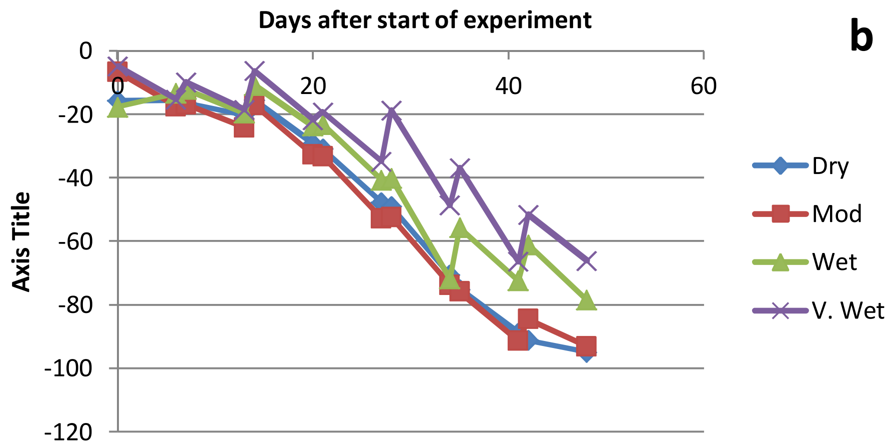
3.2.2 Results – Soil moisture variation

3.2.2.1 Soil Moisture Deficit

A range of soil moisture deficits were generated in both the high and low OM soils (Figure 34).By the end of the experiment, the dry treatment had reached a SMD of 113 mm in the high OM soil and 94 mm in the low OM soil. The maximum values in both soils declined by approximately 10 mm and 50 mm in the high and low OM soils respectively in the first 4-5 weeks of treatments suggesting that the soil was still settling in the bins and reducing the water holding capacity of the soils or that capping may have been reducing penetration of soil water. Overall, the spread of treatments was wider in the high OM soil as a result of its relatively higher water holding capacity. Unexpectedly, the SMD in the moderate treatment in both soils was similar to the un-irrigated dry treatment throughout the experiment.

Figure 34 SMD over time of experiment (a) high organic matter soil and (b) low organic matter soil.





3.2.2.2 Water loss/use

Accumulated weekly water loss

The accumulated weekly loss of water from the bins was similar for the dry treatment in both soils but was relatively greater for the irrigated treatments in the high OM soil (Table 8). By week 6 the very wet treatments were losing more water than the other irrigated treatments.

Table 8 Accumulated loss of water (mm) from the bins over the experiment.

	High OM	Low OM
Dry	92.2	83.8
Mod	123.3	98.9
Wet	136.7	112.4
V. Wet	141.0	124.1

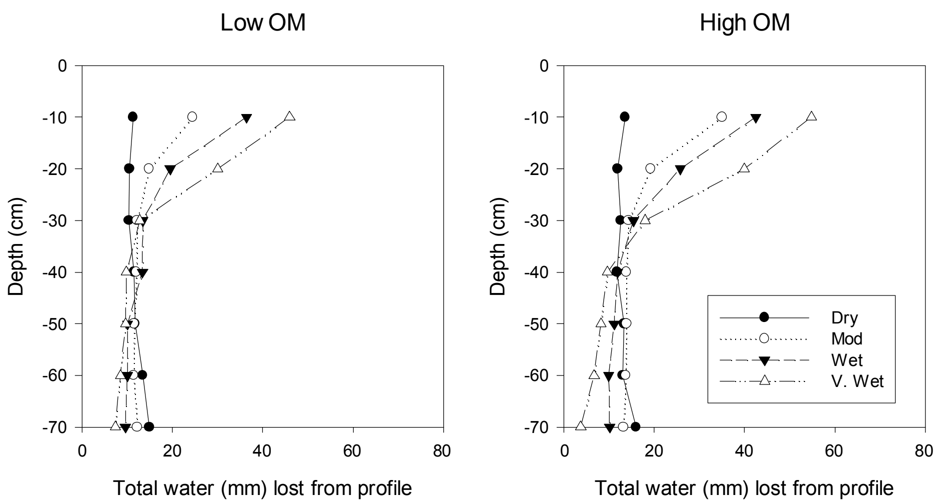
Weekly water use by depth

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 v. 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 v. 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.

Total water use by depth

Water loss varied with treatment with the greatest loss from the irrigated treatments at 10 cm depth (Figure 35). Water loss in the un-irrigated 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.

Figure 35 Total water loss (mm) calculated from weekly SMD differences.



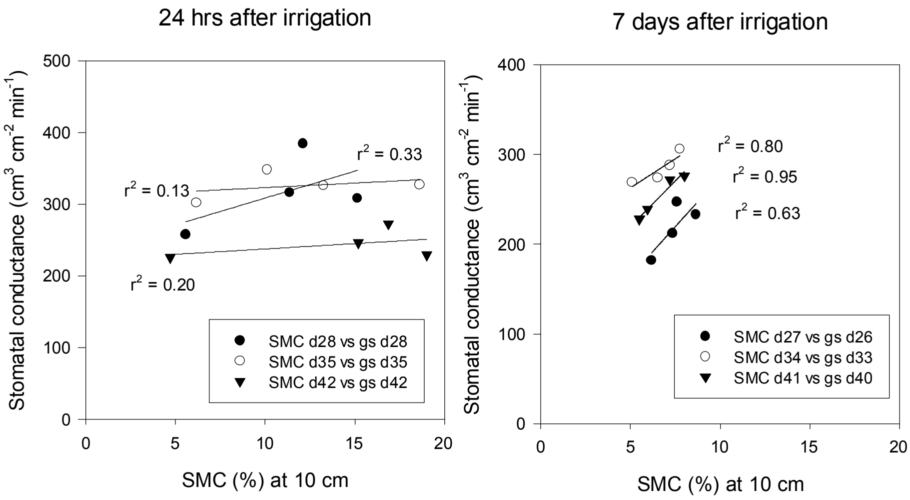
The experiment generated a wide range of SMD. As these developed, the lettuce plants accessed water from deeper in the profile. This use of progressively deeper water was observed in all treatments but was proportionally greatest in the dry treatment and least with very wet treatment. The water use in the top 20 cm was most important for the irrigated treatments but includes an unquantified proportion of evaporative loss.

3.2.3 Results: crop water status (High OM only)

3.2.3.1 Stomatal conductance

In general, the stomatal conductance of the dry treatment was lower than the irrigated treatments, but this was only significant on day 28 where the dry treatment was significantly lower than the wet treatment. There was no overall correlation observed between stomatal conductance and SMD (calculated from blocks 1, 3 and 5). However, a consistent relationship between SMD and stomatal conductance was observed on days 26, 33 and 40 taken the day before irrigation, when the differences between SMD would be relatively large. This relationship disappeared the day after irrigation i.e. days 28, 35 and 42 (Figure 36).

Figure 36 Stomatal conductance on SMD at 10 cm.



3.2.3.2 CWSI

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

3.2.3.3 RWC

The relative water content of leaves generally increased from dry to v. wet treatment at day 29, but this was not significant. By Day 43, the dry treatment had the highest RWC but this was not statistically significant. Crop water status measures based around stomatal function were variable. Stomatal conductance was correlated with SMD towards the end of the crop, when the differences in SMD were greatest between treatments. However, neither CWSI nor RWC were correlated with soil water status.

3.2.4 Results – Crop 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.

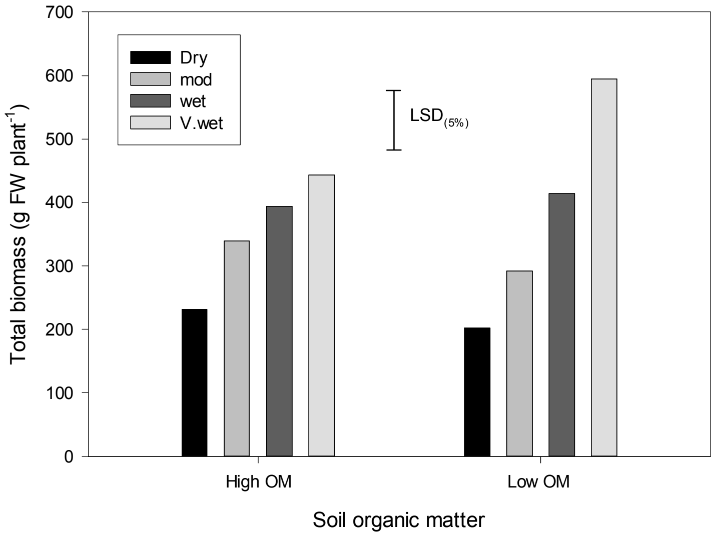
Leaf measurements did not respond to treatment and are not a good measure of soil water status.

3.2.5 Results – Harvest

3.2.5.1 Total biomass

Total biomass increased significantly with irrigation. This response was similar for both soils, with the greatest biomass produced with the v. wet treatment which at 443 g plant^{-1} in the high OM soil and 594 g plant^{-1} in the low OM soil, was two and three times greater than their respective un-irrigated treatments (Figure 37).

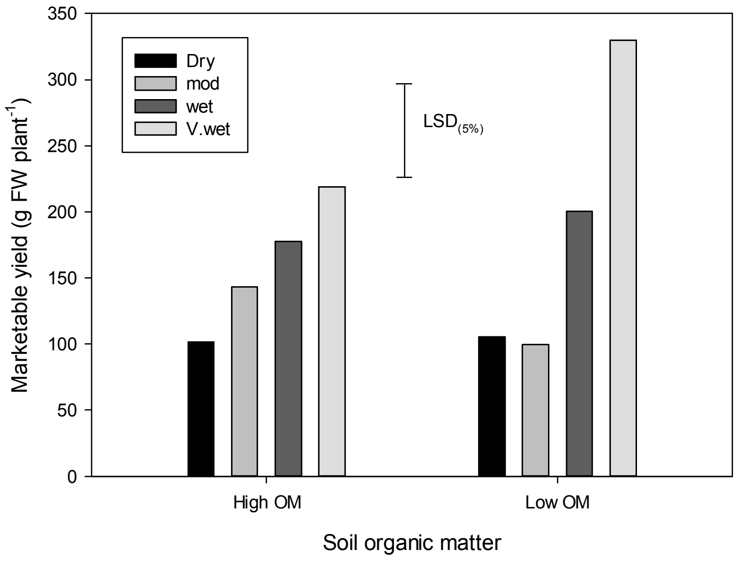
Figure 37 Average total biomass per plant (FW plant^{-1}).



3.2.5.2 Head weight

Average individual Head weight (marketable yield) responded similarly to total biomass although the relative increase in weight was greater in the low OM soil treatments (Figure 38). High OM ranged from 101.4 g (22.8 t ha^{-1}) to 219.1 g (49.2 t ha^{-1}), Low OM ranged from 99.8 g (22.4 t ha^{-1}) to 329.7 g (74.1 t ha^{-1})

Figure 38 Marketable yield expressed as average individual head fresh weight (g FW plant^{-1}).



3.2.5.3 Waste weight

The weight of waste leaves was least in the dry treatments but increased significantly with irrigation. In contrast to head weight, all three irrigated treatments produced a similar weight of waste leaves in the high OM soils although in the low OM soil the v. wet treatment produced significantly more than the other irrigated treatments.

3.2.5.4 Head size

Surprisingly, head size was similar for all treatments in the high OM soil. In the low OM soil, head size responded significantly to irrigation.

3.2.5.5 Head Dry Weight

The dry weight of heads increased with irrigation in both soils, but dry and moderate treatments were similar and significantly lighter than wet and v. wet treatments.

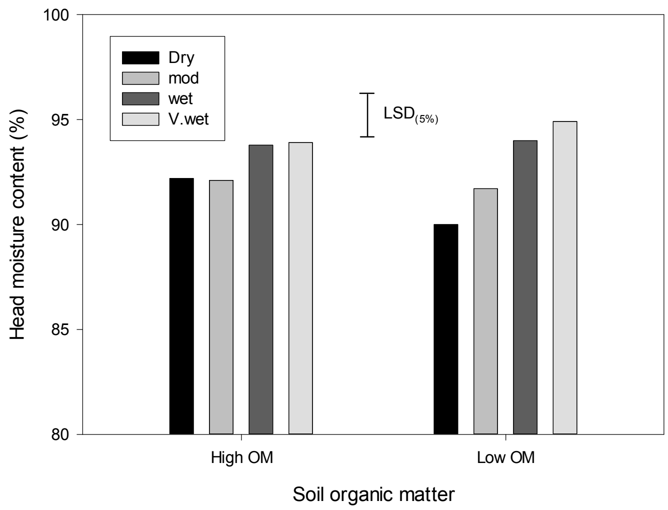
3.2.5.6 Total Dry Matter

All irrigated treatments had a similar total dry weight in the high OM soil, significantly greater than the dry treatment. In the low OM soil, total dry weight increased with irrigation.

3.2.5.7 Head Moisture Content

Irrigation led to increased water content in the heads with the response being more marked in the Low organic matter soil (Figure 39). This response was similar to head DW with moisture content of the dry and moderate treatments being similar and significantly less than wet and v. wet treatments.

Figure 39 Head moisture content (%) for the low and high organic matter treatments.



Soil OM had a significant effect on the crop response to irrigation but the overall response was similar with irrigation leading to greater biomass production and heavier heads with a higher proportion of water in them.

3.2.5.8 Irrigation Water Use efficiency

IWUE was affected by soil OM. In the low OM soil IWUE was highest at the highest irrigation treatment. At the high OM, IWUE was similar for all irrigated treatments. In the low OM soil both head and biomass IWUE was approximately two times higher than in the high OM soil at the wet and very wet treatments.

IWUE was affected by soil OM (Table 9). Plants were utilising water less efficiently to produce biomass in the high OM soil with added water but marketable yield increased consistently with added water. In the low OM soil, efficiency of water use in producing marketable yield increased with application of water although efficiency of overall plant growth (biomass) was similar amongst treatments.

Table 9 Total water applied (l/bin) and Irrigation WUE (g l^{-1}) for both biomass and head fresh weight.

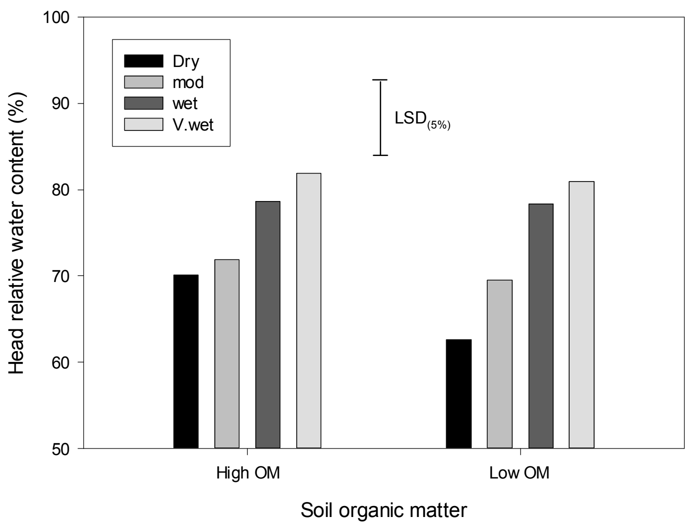
	Water applied (l bin^{-1})		Biomass IWUE (g l^{-1})		Head IWUE (g l^{-1})	
	High OM	Low OM	High OM	Low OM	High OM	Low OM
Dry	0	0	-	-	-	-
Moderate	10.2	6.1	41.8	59.4	16.3	-3.8
Wet	20.4	13.2	31.7	64.3	15.0	28.8
Very wet	28.1	24.9	30.0	63.0	16.7	36.0

3.2.6 Results – Post harvest

3.2.6.1 RWC

There was no clear pattern of response in RWC on day 1 or day 10 after harvest in the lettuce from the high OM soil. The RWC increased with irrigation treatment at day 1 for the lettuce from low OM soil but not significantly and by day 10 this response was not present. However, by day 20 lettuce from both soils showed a clear increase in RWC with irrigation with the highest RWC being measured for the v. wet treatment, significantly higher than that measured for the moderate and dry treatments (Figure 40).

Figure 40 Relative head water content of the outer leaves 20 days after harvest.



3.2.6.2 Membrane leakage

There were no significant differences in solute leakage between treatments on any sample date after harvest.

3.2.6.3 Quality assessment

There were no significant differences in any quality assessment after 1 and 10 days storage. After 20 days pinking was significantly higher in the v. wet treatment of plants grown in both soils. Differences did not appear until 20 days in storage where very wet treatments had a significantly higher RWC and level of pinking.

3.3 Lettuce (HortRhizo01)

3.3.1 Materials and methods

Iceberg lettuce plants (cv Challenger) were grown from transplants in split rhizotrons (7 x 27 x 130 cm for each independent compartment). Soil taken from the location of the polytunnel was amended with 25% (high OM soil) and passed through a screen to produce a defined uniform soil with which the rhizotrons were filled. The bins were filled on 27 July 2011 watered to saturation, allowed to settle and topped up on 5 August 2011. Rhizotrons were watered to FC and one transplant was placed in each independent compartment on 3 August 2011, treatments were started on 10 August 2011 (Day 0). The experiment finished on 9 September 2011 (Day 30).

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. These were located centrally at 20, 40, 65, 90 and 110 cm. The readings were assumed to represent the volume of soil at 0-30, 30-52.5, 52.5–72.5, 72.5-100, 100-130. The water content of the soil at FC was estimated gravimetrically before the start of the trial as 34.2%. The SMD was calculated for each zone and summed to give a total SMD 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.

3.3.1.1 Experimental design

Rhizotrons were placed in a ventilated greenhouse. Each rhizotron consisted of two duplicated independent compartments. The two treatments were randomly placed within the layout (Table 10).

Table 10 Experimental treatments and layout.

Irrigation	Treatment
Dry	1
Wet	2

Block 1	1	1	2
Block 2	1	1	2
Block 3	2	1	2
Block 4	2	1	2
Block 1	1	1	2
Block 2	1	1	2
Block 3	2	1	2
Block 4	2	1	2

3.3.1.2 Assessments

3.3.1.2.1 Soil moisture

Soil moisture was measured using a theta probe at five depths (20, 40, 65, 90 and 110 cm) in each rhizotron as described above.

3.3.1.2.2 Root growth

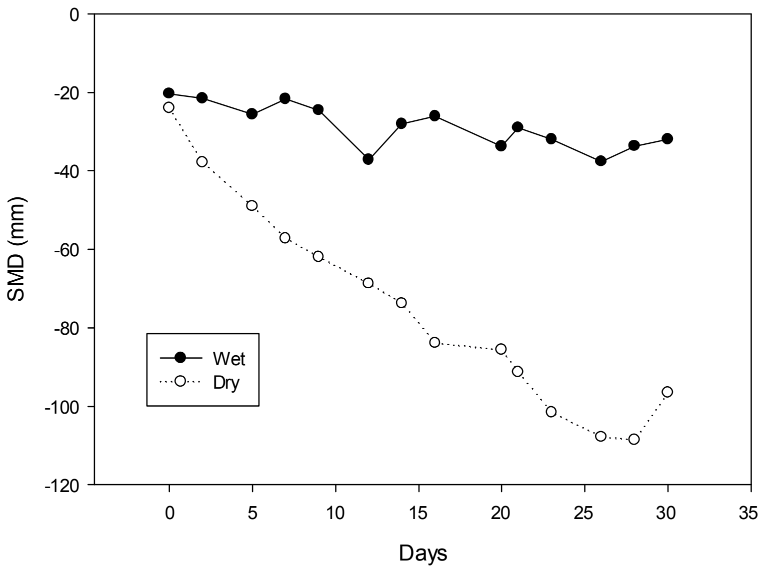
Twice a week (Tuesday and Friday) the Perspex face of the rhizotron was uncovered and a clear sheet of plastic, marked with 9 squares, each 3 x 3 cm was placed on the face and the number of cells with roots in were counted. The assessment was made at 5 cm either side of the soil moisture access holes i.e. at 15, 25, 35, 45, 60, 70, 85, 95, 105, 115 cm.

3.3.2 Results: soil moisture variation

3.3.2.1 Total SMD

A range of soil moisture deficits were generated in both treatments (Figure 41). The wet treatment did not dry to below 40 mm SMD between irrigation events. It became increasingly difficult to water the rhizotrons as the lettuce grew. By the end of the experiment, the dry treatment had reached a maximum SMD of 109 mm.

Figure 41 Total SMD over the experiment.



3.3.2.2 SMD at depth

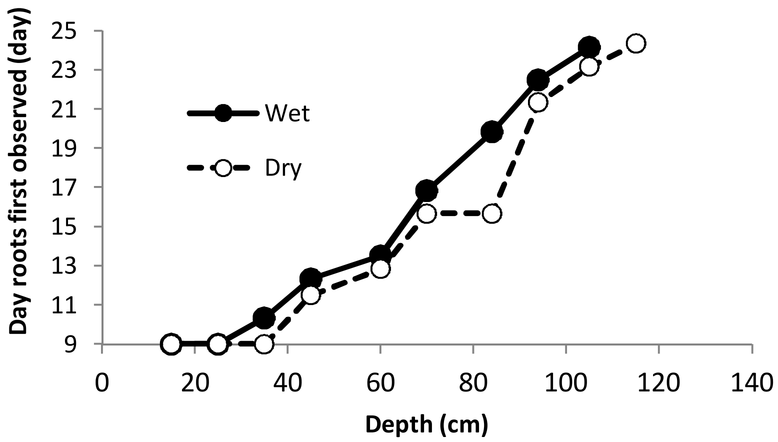
The SMD of the wet treatment was maintained above 10 mm at all depths. As expected the surface zone was drier than the rest of the soil. The SMD declined at similar rates at each depth in the dry treatment, although the surface dried more rapidly than the deeper soil.

3.3.3 Results – root growth

3.3.3.1 Rate of rooting

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 42).

Figure 42 Average days for first root to attain depth.

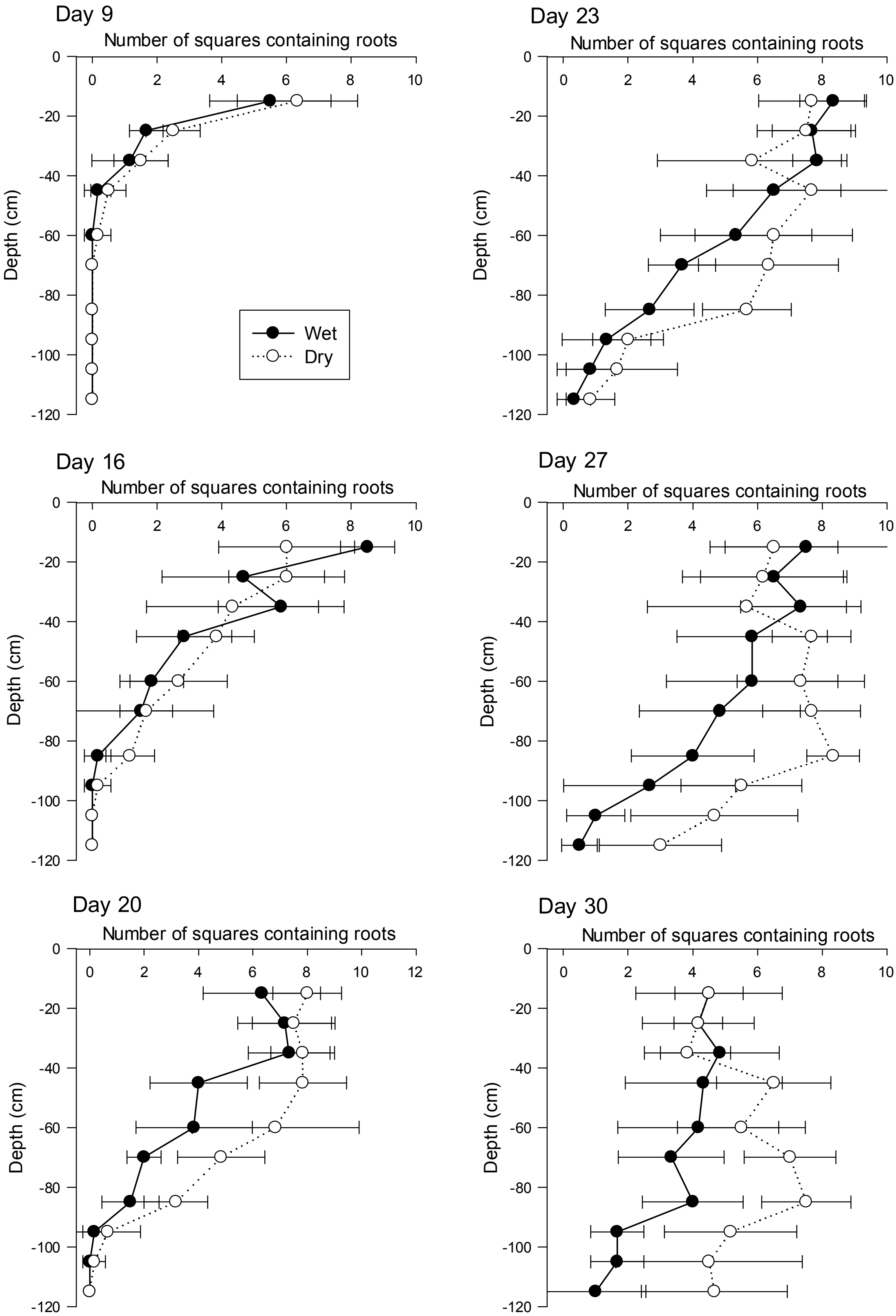


3.3.3.2 Distribution of roots

The distribution of roots was similar between the treatments after 9 and 16 days (Figure 44). 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.

Figure 43 Hortrhizo01 showing (a) face of rhizotron with cover removed and (b) rear of rhizotron with covered access holes.

Figure 44 Number of roots observed down the rooting profile in rhizotron grown lettuce.



4 Summary and conclusions

- The field observation studies on lettuces at G's and PDM and onions at Elveden during 2011 provided a very useful insight into understanding in-field soil variability at three different locations and soil types;
- The EMI scanning provided a useful technique for mapping soil variability, and for understanding the magnitude and scale of variability in each field. The Ely field was much more variable than the rest of the other fields due to the heavy clay and high organic carbon content but also due to the presence of clay rodden's across the field. For a better understanding of the causes of soil variability, the EMI scanning must be coupled and combined with soil sampling and other techniques such as the Vis-NIR spectroscopy;
- The Vis-NIR spectroscopy is a promising and useful tool to assess the spatial field variability of different elements or soil components. However this technique requires intensive laboratory soil analysis for calibrating and validating the model;
- The organic carbon content at Ely was on average 14% compared to less than 2% at Elveden and Shropshire sites. The organic carbon and soil moisture contents have shown to be the lowest on the rodden compared to the rest of the field;
- The wireless sensors provided real-time data on soil moisture content, and its variability over time with depth. A much greater range in soil moisture variability was observed at G's than at Elveden, due to differences in soil type. However, expected correlations between soil moisture and soil variability (derived from EMI scanning) were not observed – instead soil moisture was more variable within each block than between the different blocks, possibly influenced by other factors including sensor instrument siting, local dry spots, soil compaction, soil cracking around sensors and/or tensiometers and non-uniform water application;
- Assessment of irrigation performance using uniformity coefficients (CU and DU) confirmed that a high degree of irrigation management was in place on the boom irrigation systems at each site;
- Analyses of the fresh weights and plant/bulb circumference of lettuces and onions from the two field sites showed wide variation between individual blocks. The block located on the rodden was statistically different from two out of three of the blocks analyzed in the lettuce field. For the onion field difference between two of four sites was shown to be statistically different;
- The use of progressively deeper water was observed on onions and lettuces in all the irrigation treatments but was proportionally greatest in the dry treatment and least with the very wet treatment;
- Overall bulb yield and size has increased with irrigation treatments. However in high OM soil there was no increase in the very wet treatment compared to the wet treatments whereas yield has significantly increased with the same treatment in the low OM soil;
- Soil OM had a significant effect on the lettuce response to irrigation but the overall response was similar with irrigation leading to greater biomass production and heavier heads with a high proportion of water in them;
- Lettuces utilized water less efficiently to produce biomass in the high OM soil and the marketable yield increased consistently with added water;
- Lettuce pinking was significantly higher after 20 days storage with the very wet treatments in both soils. No significant differences in terms of quality was observed in any treatment after 1 and 10 days storage, and;
- Lettuce plants produce more, deeper roots in response to a developing soil moisture deficit. Lettuce roots grew to more than 1 m in 23 days.

5 References

Abdu, H.,Robinson, D., A. and Jones, S., B. (2007). Comparing bulk soil electrical conductivity determination using DUALEM-1S and EM38-DD electromagnetic induction instruments. *Soil Science Society of America Journal.* 71:189-196.

Baumhardt, R.L., R.J. Lascano, and S.R. Evett. 2000. Soil material, temperature, and salinity effects on calibration of multisensor capacitance probes. Soil Sci. Soc. Amer. J. 64(6): 1940– 1946.

Brevik, E. C. and Fenton, T. E. (2002). Influence of soil water content, clay, temperature, and carbonate minerals on electrical conductivity readings taken with an EM-38. *Soil Survey Horizons* 43, 9–13.

Corwin, D.,L., and Lesch, S.,M. (2003). Application of soil electrical conductivity to precision agriculture: Theory, principles, and guidelines. *Agronomy Journal* 95:455–471.

Corwin, D.L. and Rhoades, J.D. (1982). An Improved Technique for Determining Soil Electrical Conductivity - Depth Relations from Electromagnetic Induction Measurements. *Soil Sci. Soc. Am. J.* 46:810 - 812.

Corwin, D.L. and Rhoades, J.D. (1990). Establishing Soil Electrical Conductivity – Depth Relations from Electromagnetic Induction Measurements. *Commun. Soil Sci. Plant Anal.* 21: 871 -901.

Doolittle, J.,A., Sudduth, K.,A., Kitchen, N.,R., and Indorante ,S.,J. (1994). Estimating depths to claypans using electromagnetic induction methods. *Journal of Soil and Water Conservation* 49:572–575.

Godwin, R. J. and Miller, F. C. H. (2003), A review of the techniques for mapping within-field variability, *Biosystems Engineering*, vol. 84, no. 4, pp. 393-407

Hedley, C. B., Yule, I. J., Tuohy, M. P. and Kusumo, B. H. (2010), Proximal sensing methods for mapping soil water status in an irrigated field, Proximal Soil Sensing: Progress in Soil Science 1, DOI 101007/978-90-481-8859-8-32.

James, I.,T.,Waine, T.,W.,Bradley, R., I.,Taylor, J.,C., and Godwin, R., J. (2003). Determination of soil type boundaries using Electromagnetic Induction scanning techniques. *Biosystems Engineering* 86(4), 421-430.

Jaynes, D.,B., Novak, J.,M., Moorman, T.,B., and Cambardella C.,A. (1995). Estimating herbicide partition coefficients from electromagnetic induction measurements. *Journal of Environmental Quality* 24:36–41.

King, J.,A., Dampney, P., M., R., Lark, R., M., Wheeler, H., C. Bradley, R., I. and Mayr, T., R.(2005). Mapping Potential Crop Management Zones within Fields: Use of Yield-map Series and Patterns of Soil Physical Properties Identified by Electromagnetic Induction Sensing. *Precision Agriculture*, 6, 167:181.

Martinelli H.,P. and Osella A., M. (2010). Small-loop electromagnetic induction for environmental studies at industrial plants. *Journal of Geophysics and Engineering* **7:** 91–104.

Rhoades, J.D. (1992). Instrumental Field Methods of Salinity Appraisal. In: Topp, G.C. et al. (Ed) Advances in Measurement of Soil Physical Properties: Bringing Theory in Practice. SSSA Spec. Publ. 30, SSSA, Madison WI, USA.

Rhoades, J.D., Chanduvi, F. and Lesch, S. (Eds.). (1999). Soil Salinity Assessment. Methods and Interpretation of Electrical Conductivity Measurements. *Irrigation and Drainage Paper No 57.* FAO, Rome, Italy. 153 pp.

Rhoades, J.D., Lesch, S.M., Shouse, P.J. and Alves, W.J. (1989). New Calibrations for Determining Soil Electrical Conductivity-depth Relations from Electromagnetic Measurements. *Soil Sci. Soc. Am. Journal* 53: 74 - 79.

Slavich, P.G. (1990). Determining EC, Depth Profiles from Electromagnetic Induction Measurements *Australian Journal of Soil Research* 28: 443 - 452.

Sudduth, K.,A., Drummond, S.,T., and Kitchen N.,R. (2001). Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. *Computers and Electronics in Agriculture* 31:239–264.

Sudduth, K.,A., Kitchen N.,R., Wiebold, W.J., Batchelor, W.D., Bollero, G.A., Bullock, D.G., Clay, D.E., Palm, H.L., Pierce, F.J., Schuler, R.T., and Thelen, K. D. (2005). Relating apparent electrical conductivity to soil properties across the north-central USA. *Computer and Electronics in Agriculture*, vol.46, pp.263-283.

Waine, T. W., Blackmore, B. S. and Godwin, R. J. (2000), —Non-invasive soil property measurement for precision farming , Paper 00-SW-044, presented at AgEng 2000, 3 to 7 July 2000, Warwick, UK.

Williams, B. G. and Hoey, D.(1987). The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soils. *Australian Journal of Soil Research* 25, 21–27.

Christiansen, J. E. (1942). Irrigation by sprinkling. California Agric.Exp.Sta.Bull.670. University of California, Berkeley.

Heermann, D.F., Wallender, W.W. and Bos, G.M. (1990). Irrigation efficiency and uniformity. In : Hoffman G.J., Howell T.A., Solomon K.H:, Management of farm irrigation systems. ASAE, St Joseph,MI, 125-149.

Wang, J. and Schmugge, T.(1980). An empirical Model for the complex Dielectric permittivity of soils as a function of water content. IEEE Transactions on geoscience and remote sensing, Vol. GE-18, No.4.