Irrigation Science, January 2015, Volume 33, Issue 1, 2014, pp. 1-14
DOI: 10.1007/s00271-014-0444-2

Simulating impacts of irrigation heterogeneity on onion (*Allium cepa L.*) yield in a humid climate

Perez-Ortola, M., Daccache, A., Hess, T.M., and Knox, J.W*

Dept. Environmental Science and Technology, Cranfield University, Bedfordshire, MK43 0AL, UK

* Corresponding author: j.knox@cranfield.ac.uk

Abstract

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

Keywords: Aquacrop model; management; linear move; precision irrigation; uniformity.

1 Introduction

Onions are a food crop of major global economic importance, with annual production estimated to be around 85 million tonnes (FAO 2012). They represent the third most important vegetable crop (in terms of tonnage) after tomatoes and watermelons (FAO 2012). In arid and semi-arid regions, nearly all commercial production is dependent on irrigation (Mohammadi *et al*. 2010; Halvorson *et al*. 2008). In contrast, in humid and temperate areas, such as the UK and northern Europe, supplemental irrigation is widely used to buffer the impacts of infrequent and/or irregular rainfall during short-term droughts (Pejic *et al*. 2011) and to deal with the vagaries of unpredictable summer rainfall. Under these agroclimatic conditions, quality assurance, rather than yield, is the main driver for irrigation investment. Irrigation is used to assure high quality, continuous supplies of produce as demanded by the major retailers and supermarkets (Knox *et al*. 2010a). In the UK, a changing climate with increasing aridity and more unpredictable rainfall suggests that supplemental irrigation to offset the impacts of increased droughtiness on crop yield and quality will become much more widespread and important (Daccache *et al*. 2012).

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

Onion yield and quality are principally affected by local weather and soil conditions, in combination with fertilisation practices, the incidence of pests and disease, storage diseases and irrigation (Mohammadi e*t al*. 2010; Kumar *et al*. 2007). Recent studies have also identified water quantity and the timing of irrigation as likely to have major impacts on yield and quality (Jiménez *et al*. 2010; Enciso *et al*. 2009; Martín de Santa Olalla *et al*. 2004). There is also widespread industry and scientific evidence on the need to increase water efficiency in irrigated agriculture (more 'crop per drop') with improvements in field-scale water and soil management often cited as key priorities to increase productivity whilst minimising the environmental impacts associated with irrigation (Monaghan *et al*. 2013).

There is also growing scientific interest in the role that precision irrigation (PI) can make in improving crop productivity and increasing water and energy efficiency (Smith *et al*. 2010). Most progress has been made in arid and semi-arid climates in high-value production systems where irrigation costs coupled with concerns regarding water scarcity have stimulated PI innovation and development. Historically, farmers have ignored soil and crop variability and attempted to apply water as uniformly as possible. Most research has thus focussed on reducing the impacts of irrigation heterogeneity on production. But PI technology is now capable of applying water non-uniformly or differentially to match in-field variations, for example, due to soil, crop and/or topography (Daccache et al. 2014). Such developments have important implications for understanding uniformity impacts on yield. For example, research in Spain on sugar beet by Ortiz et al (2012) showed how the uniformity of accumulated irrigation under a centre pivot can be significantly higher compared to assessments of individual irrigation events. Research by Lacey (2006) in a humid environment similarly highlighted the limitations of assessing performance (uniformity) from individual irrigation events on crop yield and for high value crops such as carrots, more importantly, the impacts on quality (shape, size).

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

2 Modelling onion growth with AquaCrop

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

2.1 AquaCrop model description

The AquaCrop model was developed based on the methodology of Doorenbos and Kassam, 1979) and later also adopted by the FAO irrigation scheduling model CROPWAT (Smith, 1992), whereby crop yield is estimated as a response to crop evapotranspiration (ETcrop). A detailed description of the fundamental model components is given in Raes *et al*. (2009) and Steduto *et al*. (2009). AquaCrop has previously been used to explore irrigation scheduling in vegetables including tomato in Italy (Rinaldi *et al*. 2011), cabbage in Burkina Faso (Wellens *et al*. 2013) and extensive crops such as wheat in Canada and the USA (Mkhabela and Bullock, 2012; Nielsen *et al*. 2012) and maize in India and the USA (Nielsen *et al*. 2012; Abedinpour *et al*. 2012). These studies have shown that AquaCrop can be used to refine farmer approaches to improve irrigation scheduling and management. The research literature confirms that the model also provides accurate yield prediction considering the limited input data requirement necessary for model parameterisation.

2.2 Model parameterisation, calibration and validation

Between 2010 and 2012, a set of replicated irrigation trials on onion (cv *Arthur*) were conducted in a polytunnel environment at Broom’s Barn Research Centre (Latitude 52.61°N; Long 0.56°E; 75 m asl), Suffolk, UK. A detailed description of the trials is given in Lacey and Ober (2011). A brief description of the datasets used for model parameterisation, calibration and validation together with information relating to measurement of canopy cover (CC), biomass, final yield and soil moisture content (SMC) are included here for convenience.

The experiments were conducted on a loamy sand soil. Onions were drilled at a targeted planting density of 52 plants per m^2 between 18^{th} and 21^{st} March and harvested between 13^{th} and 24^{th} September in 2010, 2011 and 2012, respectively. The polytunnel shelter was installed between late April and early May each year to exclude rainfall and thus control the effects of irrigation on plant response. After polytunnel erection, irrigation was the only water input into the experiments. The trials were designed to evaluate the impact of different irrigation scheduling regimes on crop yield, quality and storability, in order to establish best practice guidelines for UK onion growers. Initially, eight treatments were defined (Lacey and Ober, 2011) (Table 1a) which were modified after the first year to reflect more closely UK typical practices (Table 1b). Each irrigation treatment had three replicates (i.e. 24 plots in total). Each plot constituted an onion bed measuring 2.03m in width and 8 m in length (16 m^2). The total number of plants per plot was 832.

Daily weather (maximum and minimum temperature, relative humidity, radiation, and wind speed) were recorded under the polytunnel using an automatic weather station. Daily temperature and reference evapotranspiration (ETo) were also recorded from a nearby automatic weather station on the same site. Figure 1 provides a meteorological summary for the period during which the trials were conducted, with data from the polytunnel for the experimental period compared against 11 years’ historical records (1992-2012) from the adjacent outdoor weather station. Under the tunnels, solar radiation and wind-speed were found to be lower than outside, but temperature was very similar. Consequently, reference evapotranspiration (ETo) was 7 to 8% lower than outside in 2010 and 2011 and 3% in 2012 (Lacey and Ober 2011; 2012; 2013) especially between June and August.

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

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

The AquaCrop model was parameterized using a combination of the experimental field data collected by Lacey and Ober (2010, 2011) together with data for onions (*cv Arthur*) (e.g. base temperature, crop coefficient and seasonal variation, root characteristics, harvest index) published in the science literature. The model was calibrated using a trial and error approach on six of the eight irrigation treatments conducted in 2010. Table 2 summarises the crop parameters used in the AquaCrop model following parameterization and calibration. Crop water productivity (WP) is an important input parameter required for AquaCrop as it is a water driven model. In our study, we used experimental data from Lacey and Ober (2011) to estimate WP for all treatments in 2010, the calibration period. An average value of 19 g/m^2 was derived (Table 2).

The model was validated against independent data from eight of the irrigation treatments from 2011 and 2012. Two irrigation treatments (extreme water deficits in 2010, G1 and H1) were not considered because they did not represent typical onion crop production. Figure 2 shows the simulated and observed onion yields for the model (2010) and validation (2011, 2012) periods.

2.3 Model performance

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

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

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

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

Where:

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

The standard deviation (SD) was also calculated. The model fit was considered to be excellent if the RRMSE was less than 10%, good if it was between 10% and 20%, fair if it was greater than 20% and less than 30%, and poor if the values were greater than 30% (Jamieson 1991).

The ME generates values that range from negative to 1. The closer the value is to 1, the greater is the robustness of the model (Loague and Green 1991).

3 Irrigation uniformity

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

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

Where x_i is the individual records, and X the average value of that irrigation evaluation which coincided with the scheduled depth. The individual catch-can measurements were plotted as a histogram (Figure 3). For the linear move, nearly half (50%) the observations deviated from the design (scheduled) application by between -5% and +5%; for the boom the equivalent deviation was a third (33%). Further analysis showed that the coefficient of variations (CV) for the linear move and boom were 17% and 23%, respectively.

4 Scenario modelling

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

4.1 Agronomic conditions

Two soils, a sand and light sandy loam, were chosen and their textural and water holding characteristics defined (Table 3). For all scenarios, a fixed planting date (1^{st} March) and a planting density of 50 plants per m^2 were assumed to match farmer practice. For each soil type, an irrigation schedule as recommended by commercial agronomists providing scheduling advice to farmers was used; this was defined to maximise both yield and quality, assuming that the crop cycle is split into two stages (i) canopy development, and (ii) after bulbing (Table 3). Irrespective of soil type, irrigation was stopped two weeks prior to harvest to allow the mature crop to dry, a practice commonly adopted by commercial growers, and to avoid structural soil damage from harvesting machinery.

4.2 Weather conditions

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

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

Where:

$PSMD_i$ is the PSMD on day *i*, and ETo_i and R_i are reference evapotranspiration and rainfall on day *i*.

Five individual station-years were then selected to correspond to years with the lowest and highest $PSMD_{max}$ and those with 20%, 50% and 80% probabilities of exceedance (Table 4). These contrasting climate years are referred to as 'very wet', 'average wet', 'average', 'average dry' and 'very dry', respectively.

4.3 Irrigation system

Two overhead application methods, a mobile hose reel fitted with a boom and a linear move irrigation system, were included in the study, as described previously.

4.4 Simulating 'uniform' and 'non-uniform' irrigation

The AquaCrop model was used to estimate irrigation need and yield for brown onion (*cv Arthur)* for the two soil types and five weather years assuming 'uniform' irrigation. This represented the reference or 'baseline' condition. Probability distributions from the on-farm irrigation evaluation (Figure 3) were then used to generate 100 individual datasets for each of the five weather years, to represent 'typical' imperfect (i.e. non-uniform) irrigation. Each dataset contained information on the likely variation in depth of water applied (mm) for each scheduled irrigation event. A script was written using the statistical environment R (http://www.r-project.org/) to produce AquaCrop model compatible input files by combining the reference irrigation schedule with the random variations derived from the probability distribution (Figure 3). Two thousand AquaCrop input irrigation files were thus generated; comprising 100 statistically derived irrigation distributions, for two irrigation systems (boom and linear move) and five statistically defined weather years (i.e. very wet, average wet, average, average dry, and dry) on two soils (sand, sandy loam).

The AquaCrop model was then re-run using the 'non-uniform' irrigation datasets. Yield differences between 'uniform' and 'non-uniform', by soil type and weather year, were derived. For all simulations, the simulated soil conditions in Aquacrop were assumed to be at field capacity on 1st January each year, and for each soil type, the topsoil characteristics were also assumed to be uniform through depth.

5 Results and discussion

5.1 Model parameterisation

Visually, the simulated data for soil moisture content and canopy cover correlate well to the observed values (Figure 4) for both the calibration and validation periods. Table 5 summarises the calculated values for the RMSE, RRMSE and ME, as well as the standard deviation (SD) of the observed yield. The estimates are shown by year and for all years combined. The RMSE varies between 0.64 and 1.06 t DM ha^{-1}, which corresponds with the range of standard deviation (0.62-1.43). The ME values range from -0.06 to +0.52. Overall, the model performance is therefore considered good, as shown by the RRMSE values of between 10 and 20% (Table 5) and shown in Figure 5. The model matched observed yield values for those irrigation treatments where the irrigation was triggered at 50% AWC during the stage of canopy development. A slight mismatch (average deviation of -8%) between observed and simulated yield occurred when irrigation was applied more frequently at a lower soil water deficit. The model also showed very good correlation (R^2 0.93) in simulating water content in the root zone in response to irrigation and crop transpiration. The model's ability to simulate crop development (using crop cover as an indicator) was good. There are no other directly comparable results for onion, but other studies using the AquaCrop model have shown values for RRMSE of 22.6% and ME of 0.92 (Rinaldi et al. 2011), normalized RMSE (nRMSE) values of between 4 and 13% (Wellens et al. 2013) and an R^2 value of 0.66 and RMSE of 743 kg ha^{-1} for wheat (Mkhabel and Bullock 2012).

5.2 Uniform irrigation

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

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

5.3 *Non-uniform irrigation*

The onion yield for the 2000 simulated seasons are summarised in Figure 6 as a box and whisker plot. Onion production values for each scenario and irrigation system did not correspond to a normal distribution, therefore, a Kruskal-Wallis (1952) test was undertaken to identify any significant differences between groups (Table 7). Figure 6 and the statistical analyses show that the simulated yield on sandy soils were always higher than on a sandy loam; average yield produced under the linear move irrigation application system was always greater than under a mobile boom system. Yield production related to the climate year showed a similar pattern to that for uniform irrigation. The highest yield and lowest variability (IQR) was obtained under the wettest climate conditions. The greatest variability and lowest yield occurred for both soils under 'very dry' agroclimatic conditions. During drier conditions, irrigation was supplied through very frequent applications (17 irrigation events on the sandy soil and 15 on the sandy loam) compared to wetter conditions, thus exacerbating the effects of the irrigation non-uniformity. In wetter years, when irrigation is less frequent, rainfall compensates for the fewer irrigation applications. The yield variability predicted under the boom application system was greater than for a linear move system.

The factor (soil, irrigation and weather year) and their individual interaction (soil-year, and year-irrigation) were found to be significant as well as the triple interaction ($P < 0.05$). The interactions between soil and weather condition resulted in significant differences between all combinations. Table 7 presents the significance groups that result from the analysis of the triple (soil, weather and irrigation system) interactions and adds statistical evidence to the data shown in Figure 6. The highest yield was produced during the 'very wet' season on sandy soils, and the lowest during the 'very dry' season on a sandy loam soil. The study of the combined effects on yield production of irrigation non-uniformity produced by the two irrigation systems and the weather conditions, showed no significant differences during the extreme seasons ('very wet' and 'very dry') nor during the 'average wet' year. However, during the 'average' and 'the average dry' seasons the differences in average yield were significant. In those cases yield produced under the irrigation non-uniformity of linear moves was on average 60 and 40 kg DM ha^{-1} greater than under the boom non-uniformity.

The last part of the analysis considered all possible interactions between the three factors. The greatest variability in yield occurred under boom irrigation systems in 'very dry' conditions (IQR of 0.29 t DM ha^{-1}) on sandy loam, followed by the same conditions on a sandy soil (IQR of 0.22 t DM ha^{-1}), boom on sandy loam during and 'average dry' year (0.22 t DM ha^{-1}) and linear move on sandy loam during 'very dry' conditions (0.18 t DM ha^{-1}). The lowest variability occurred under hose reel fitted with boom for the wettest conditions (IQR<0.05 t DM ha^{-1}). These results show that during 'average dry' and 'average' weather conditions, both factors, soil type and irrigation system, have an effect on onion yield production. For an 'average dry' year, highest yield would be produced on sandy soils, contrary to under 'average' weather conditions. Onion production regardless of soil type would be higher under irrigation applied by linear move systems. Additionally, these results point out that during a 'very dry' season, yield would only be significantly different between irrigation systems on sandy soils. Under 'average wet' and 'very wet' weather conditions, significant differences occur only between soils.

5.4 *Yield implications due to irrigation heterogeneity*

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

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

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

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

5.5 Methodological limitations

Crop growth models are powerful tools from which growers and the wider industry can gain significant benefit. They can assist in decision-making processes such as scheduling irrigation, or choosing from a variety of crops under certain conditions or restrictions (e.g. extreme weather conditions, water restrictions, energy or water price increases). Such models can also be used to forecast yield production and make decisions about storage time and capacity. In this study, the modelling has facilitated the assessment of several factors which were known to impact on onion cropping, yield and quality in the context of evaluating the potential benefits of precision irrigation. This work focussed on the effects of water and weather variability on yield; however, other parameters such as spatial variability in soils, the irrigation schedules used and the management practices being adopted could also be studied.

For crop modelling (calibration, validation and scenario modelling), no ‘set’ planting was considered, only seed drilling. In addition, fertilisation practices were also assumed to be optimal; accordingly, no limiting effects of nutrient stress were considered. The AquaCrop model does not simulate pests or weeds; therefore the modelled crop consisted of a well fertilised, pest, disease and weed free crop. Onion bulb initiation is determined by multiple factors including photoperiod (Brewster *et al*. 1977; Lancaster *et al*. 1996). The AquaCrop model does not include the influence of day light duration or light intensity. This limits its accuracy for bulb initiation prediction. Certain assumptions were made to simplify the scenario modelling process. Regardless of climatic conditions, the planting date in each year was fixed, but in practice, it varies depending on soil and atmosphere temperature, soil moisture content and the farmers' interpretation of the short-term weather forecast.

Despite these limitations, the AquaCrop model has been shown to perform well when simulating yield response to water for onions. However, it does not provide a direct estimate of crop quality. For onions, the probability of fungal disease, regrowth, or lack of maturity due to wet conditions at the end of the season can be interpreted by using soil moisture data, crop stage development and the time of maturity. Other quality parameters such as bulb size distribution are also not predicted by the model. These results could be estimated by combining simulated final yield with planting density such as the work by de Visser and van den Berg (1998) in their physiology based onion growth model ALCEPAS (de Visser 1994).

6 Conclusion

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

Acknowledgement

The authors acknowledge the technical support and provision of experimental field data from Tim Lacey and Eric Ober and contributions from growers involved in the industry survey. The authors also thank Andrew Francis and staff at Elveden Estate (Norfolk) for provision of field sites, farm data and extensive technical support during the course of the research. The research was funded by Defra Hortlink (HL0196).

References

Abedinpour M, Sarangi A, Rajput TBS, Singh M, Pathak H, Ahmad T (2012) Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. *Agricultural Water Management* 110: 55-66.

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper No 56. Food and Agriculture Organization of the United Nations (FAO). Rome, Italy.

ASAE (2003) Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles. ANSI/ASAE S436.1 DEC01.

Brewster JL, Salter PJ, Darby RJ (1977) Analysis of growth and yield of overwintered onions *Journal of Horticultural Science* 52: 335-346.

Daccache A, Keay C, Jones RJA, Weatherhead EK, Stalham MA, Knox JW (2012). Climate change and land suitability for potato production in England and Wales: impacts and adaptation. *Journal of Agricultural Science* 150(2): 161-177.

Daccache A, Knox JW, Weatherhead EK, Daneshkhah A, Hess TM (2014) Implementing precision irrigation in a humid climate - recent experiences and on-going challenges *Agricultural Water Management* (DOI: 10.1016/j.agwat.2014.05.018).

De Visser CLM, van den Berg W (1998) A method to calculate the size distribution of onions and its use in an onion growth model. *Scientia Horticulturae* 77(3-4): 129-143.

De Visser CLM (1994) Alcepas, an onion growth-model based on sucros87 .1. Development of the model. *Journal of Horticultural Science* 69: 501-518.

Doorenbos J, Kassam AH (1979) Yield Response to Water. FAO Irrigation and Drainage Paper 33.

Enciso J, Wiedenfeld B, Jifon J, Nelson S (2009) Onion yield and quality response to two irrigation scheduling strategies. *Scientia Horticulturae* 120(3): 301-305.

FAO (2012) http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor. Accessed 12 May 2014.

Halvorson AD, Bartolo ME, Reule CA, Berrada A (2008) Nitrogen effects on onion yield under drip and furrow irrigation. *Agronomy Journal* 100: 1062-1069.

Jamieson PD (1991) A test of the computer simulation model ARCWHEAT 1 on wheat crops grown in New Zealand. *Field Crops Research* 27: 337-350.

Jiménez M, De Juan JA, Tarjuelo JM, Ortega JF (2010) Effect of irrigation uniformity on evapotranspiration and onion yield *Journal of Agricultural Science* 148(02):139–157.

Knox JW, Rodriguez-Diaz JA, Weatherhead EK, Kay MG (2010a) Development of a water strategy for horticulture in England and Wales *Journal of Horticultural Science and Biotechnology* 85 (2): 89-93.

Knox JW, Rodríguez Díaz JA, Nixon DJ, Mkhwanazi M (2010b) A preliminary assessment of climate change impacts on sugarcane in Swaziland *Agricultural Systems* 103(2):63–72.

Knox JW, Kay MG, Weatherhead EK (2012) Water regulation, crop production, and agricultural water management - Understanding farmer perspectives on irrigation efficiency *Agricultural Water Management* 108: 3-8.

Kruskal WH, Wallis WA (1952) Use of ranks in one-criterion variance analysis *Journal of the American Statistical Association* 47(260): 583-621.

Kumar S, Imtiyaz M, Kumar A (2007) Effect of differential soil moisture and nutrient regimes on postharvest attributes of onion (Allium cepa L.) *Scientia Horticulturae*, 112(2):121-129.

Lacey TR (2006) Improving irrigation efficiency: raingun performance in field-scale vegetable production PhD thesis (unpublished), Cranfield University, Bedford, UK.

Lacey TR, Ober E (2011) Impact of irrigation practices on Rijnsburger bulb onion husbandry, quality and storability - II FV 362a. Annual Report, Year 1.

Lacey TR, Ober E (2012) Impact of irrigation practices on Rijnsburger bulb onion husbandry, quality and storability - II FV 362a. Annual Report, Year 2.

Lacey TR, Ober E (2013) Impact of irrigation practices on Rijnsburger bulb onion husbandry, quality and storability - II FV 362a. Annual Report, Year 3.

Lancaster JE, Triggs CM, De Ruiter JM, Gandar PW (1996) Bulbing in onions: photoperiod and temperature requirements and prediction of bulb size and maturity. *Annals of Botany* 78: 423-430.

Loague K, Green RE (1991) Statistical and graphical methods for evaluating solute transport models: Overview and application *Journal of Contaminant Hydrology* 7: 51-73.

Martín de Santa Olalla F, Domínguez-Padilla A, López R (2004) Production and quality of the onion crop (Allium cepa L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate *Agricultural Water Management* 68(1): 77-89.

Misra R, Raine S, Pezzaniti D, Charlesworth P, Hancock N (2005) A scoping study on measuring and monitoring tools and technology for precision irrigation. Irrigation Matters Series 01/05.

Mkhabela MS, Bullock PR (2012) Performance of the FAO AquaCrop model for wheat grain yield and soil moisture simulation in Western Canada *Agricultural Water Management* 110: 16-24.

Mohammadi J, Lamei J, Khasmakhi-Sabet A, Olfati JA, Peyvast G (2010) Effect of irrigation methods and transplant size on onion cultivars yield and quality *Journal of Food Agriculture and Environment* 8: 158-160.

Monaghan JM, Daccache A, Vickers L, Hess TM, Weatherhead EK, Grove IG, Knox JW (2013) More ‘crop per drop’ – constraints and opportunities for precision irrigation in European agriculture *Journal Science of Food and Agriculture* 93(5): 977-80.

Nielsen DC, Miceli-Garcia JJ, Lyon DJ (2012) Canopy cover and leaf area index relationships for wheat, triticale and corn. *Agronomy Journal* 104(6): 1569-1573.

Ortiz JN, Tarjuelo JM, de Juan JA (2012) Effects of two types of sprinklers and height in the irrigation of sugar beet with a centre pivot *Spanish Journal of Agricultural Research* 10(1): 251-263.

Pejic B, Gvozdanovic-Varga J, Milic S, Ignjatovic-Cupina A, Krstic D, Cupina BB (2011) Effect of irrigation schedules on yield and water use of onion (Allium cepa L.) *African Journal of Biotechnology* 10: 2644–2652.

Perez-Ortola M (2014) Modelling the impacts of in-field soil and irrigation variability on onion yield. MPhil thesis, Cranfield University, UK.

Raes D, Steduto P, Hsiao TC, Fereres E (2009) AquaCrop-The FAO crop model to simulate yield response to water: II. Main algorithms and software description *Agronomy Journal* 101: 438-447.

Raine SR, Meyer WS, Rassam DW, Hutson JL, Cook FJ (2007). Soil-water and solute movement under precision irrigation: knowledge gaps for managing sustainable root zones. *Irrigation Science* 26: 91-100.

Rinaldi M, Garofalo P, Rubino P, Steduto P (2011) Processing tomatoes under different irrigation regimes in Southern Italy: agronomic and economic assessments in a simulation case study *Italian Journal of Agrometeorology* 3: 39–59.

Rodríguez Díaz JA, Weatherhead EK, Knox JW, Camacho E (2007) Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain *Regional Environmental Change* 7(3): 149-159.

Smith M (1992) CROPWAT: A computer program for irrigation planning and management. *FAO Irrigation and Drainage* Paper No. 46.

Smith RJ, Baillie JN, McCarthy AC, Raine SR, Baillie CP (2010) Review of precision irrigation technologies and their application. National Centre for Engineering in Agriculture. Publication 1003017/1, USQ, Toowoomba.

Steduto P, Hsiao TC, Raes D, Fereres E (2009) AquaCrop - The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal* 101(3): 426-437.

Wellens J, Raes D, Traore F, Denis A, Djaby B, Tychon B (2013) Performance assessment of the FAO AquaCrop model for irrigated cabbage on farmer plots in a semi-arid environment *Agricultural Water Management* 127: 40-47.

Zekri M, Parsons LR (1999) Determination of field capacity in a Florida sandy soil and drainage time at different depths *HortTechnology* 9: 258-261.

Table 1a Irrigation regimes for experimental onion trials conducted at Broom's Barn in 2010 (Lacey and Ober, 2011).

2010 Treatments		**From start to bulb initiation**		**From bulb initiation**		**Stop Irrigation at**
		Trigger	**Target App**	**Trigger**	**Target App**	
A1	Typical	50% AWC	Return to FC	75% AWC	Return to FC	50% FO
B1	Typical, no extra stress	50% AWC	Return to FC	50% AWC	Return to FC	50% FO
C1	Typical, no extra stress, extended	50% AWC	Return to FC	50% AWC	Return to FC	100% FO, 50% dead
D1	Less more often, no extra stress	25% AWC	Return to FC	50% AWC	Return to FC	50% FO
E1	Less more often, no extra stress, extended	25% AWC	Return to FC	25% AWC	Return to FC	100% FO, 50% dead
F1	Excess	12.5% AWC	Return to FC	12.5% AWC	Return to FC	100% FO, 50% dead
G1	Stress	75% AWC	50%AWC	75% AWC	50%AWC	50% FO
H1	No irrigation	-	-	-	-	-

Table 1b Irrigation regimes for experimental onion trials conducted at Broom's Barn in 2011 and 2012 (Lacey and Ober, 2012, 2013).

2011 and 2012 Treatments		**From start to bulb initiation**		**Bulb initiation to egg stage**		**Egg stage to stop**		**Stop Irrigation at**
		Trigger	**Target App**	**Trigger**	**Target App**	**Trigger**	**Target App**	
A2/3	Typical, end season stress	50% AWC	Return to FC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
B2/3	Typical, mid+end season stress	50% AWC	Return to FC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO
C2/3	Typical, early+end season stress	75% AWC	50% of AWC	50% AWC	Return to FC	75% AWC	50% of AWC	50% FO
D2/3	Less more often, no stress	25% AWC	Return to FC	25% AWC	Return to FC	25% AWC	Return to FC	50% FO
E2/3	Less more often, end season stress	25% AWC	Return to FC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
F2/3	Less more often, mid+end season stress	12.5% AWC	Return to FC	12.5% AWC	Return to FC	75% AWC	50% of AWC	50% FO
G2/3	Less more often, early+end season stress	75% AWC	50% of AWC	25% AWC	Return to FC	75% AWC	50% of AWC	50% FO
H2/3	Stress all season	75% AWC	50% of AWC	75% AWC	50% of AWC	75% AWC	50% of AWC	50% FO

Note: AWC: Available Water Content, FC: Field Capacity, FO: Fall over.

Table 2 Variables used to parameterise the AquaCrop model for brown onion (*cv. Arthur*).

Parameter	Value	Unit	Source
Temperature requirements			
Base Temperature to estimate GDD	6	°C	Bossie et al. (2009)
Total crop cycle	1450	GDD	-
Crop response to soil water depletion			
Upper threshold for canopy expansion	0.3*	soil water depletion fraction	
Lower threshold for canopy expansion	0.65*	soil water depletion fraction	
Upper threshold for canopy senescence	0.92*	soil water depletion fraction	
Crop development			
from sowing to emergence	60	GDD	Lacey and Ober (2011, 2012)
from sowing to maximum rooting depth	343	GDD	Lacey and Ober (2011, 2012)
from sowing to start tuber formation	816	GDD	Lacey and Ober (2011, 2012)
from sowing to start senescence	1263	GDD	Lacey and Ober (2011, 2012)
from sowing to maturity (length of crop cycle)	1450	GDD	Lacey and Ober (2011, 2012)
CGC for GGD: Increase in canopy cover	0.07508	Fraction soil cover per growing-degree day	Indirect estimates derived from crop stage length and max CC
CDC for GGD: Decrease in canopy cover	0.05365	Fraction per growing-degree day	Indirect estimates derived from crop stage length and max CC
Crop coefficient			
Crop coefficient when canopy is complete but prior to senescence	0.95		Modified between 0.9 (Piccini et al. 2009) and 1.05 (Allen et al. 1998)
Decline of crop coefficient as a result of ageing, nitrogen deficiency	0.8	%/day	(Piccini et al. 2009)
Crop rooting			
Maximum effective rooting depth	0.35 (range 0.18-0.40)	m	Drinkwater and Janes (1955) and Greenwood et al. (1982)
Shape factor describing root zone expansion	30	-	Lacey and Ober (2011; 2012)
Max root water extraction in Q1 and Q4of root zone	Calculated by AquaCrop for a water uptake distribution of 40%, 30%, 20%, 10% in Q1,Q2,Q3 and Q4		
Effect of canopy cover in reducing soil evaporation in late season	60	%	Lopez-Urrea et al. (2009) determined 77% for crops where maximum CC is 72%
Maximum canopy cover (CCx)	0.65	-	Lacey and Ober (2011, 2012)
Crop Water Productivity (WP) normalized for climate and CO_2	19	g/m^2	Estimated from Lacey and Ober (2011, 2012)
Reference Harvest Index (HIo)	80	%	Laboratory measurement

*These values determine the range of RAW at which canopy expansion is reduced.

Table 3 Soil characteristics and irrigation schedule used for simulating UK onion cultivation on a sandy and light sandy loam soil.

Soil characteristic	Sand[1]	Light sandy loam[2]
Thickness (m)	4.0	4.0
Volume (%) at saturation	36.0	39.5
Volume (%) at field capacity	13.0	19.0
Volume (%) at wilting point	6.0	9
Ksat (mm/day)	1500.0	650
Readily evaporative water from top layer (%)	2	7
Restricting soil layer inhibiting root zone expansion	No	No
Irrigation schedule		
During canopy development	16 mm at 16 mm SMD[3]	23 mm at 23 mm SMD
After bulbing	23 mm at 23 mm SMD	29 mm at 29 mm SMD

[1] Average value for sand ranks (Allen et al., 1998)

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

[3] Soil Moisture Deficit

Table 4 Summary of selected weather stations and data used for defining each climate year.

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

Table 5 RMSE (t/ha), RRMSE (%), ME and standard deviation (SD) for AquaCrop model simulated and observed onion yields, based on experimental data from 2010, 2011 and 2012.

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

Table 6 Simulated irrigation water requirement (mm) and yield (t DM ha-[1]) for brown onions (*cv. Arthur*) for each climate year, by soil type, assuming perfect (100% uniform) irrigation.

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

Table 7 Summary outputs from the Kruskal-Wallis (1952) analysis. Analysis shows the average yield for groups considering the interactions between three factors (soil, climate year and irrigation method) and their interquartile range (IQR). Letters indicate whether the groups are significantly different.

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

Figure 1 Monthly mean temperature (^{0}C) and reference evapotranspiration ETo (mm) at Broom's Barn Research Centre for the experimental trials (polytunnels) (2010-12) and adjacent weather station (outside) (1992- 2012).

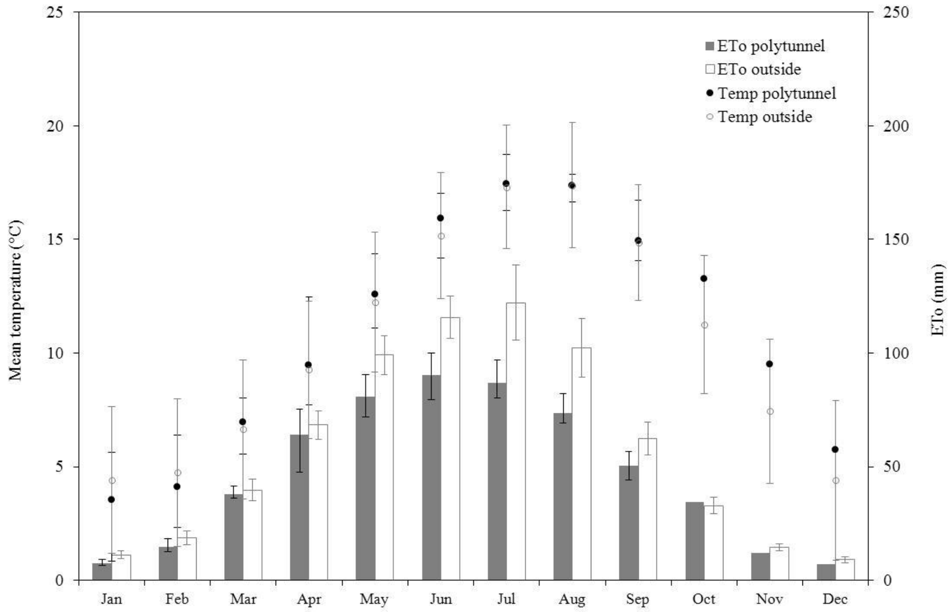

Figure 2 AquaCrop model simulated and observed brown onion (*cv. Arthur*) yield (t DM per ha) for selected irrigation treatments (Lacey and Ober, 2010; 2012) for the calibration (2010) and validation (2011-12) periods. Error bars show the maximum and minimum observations.

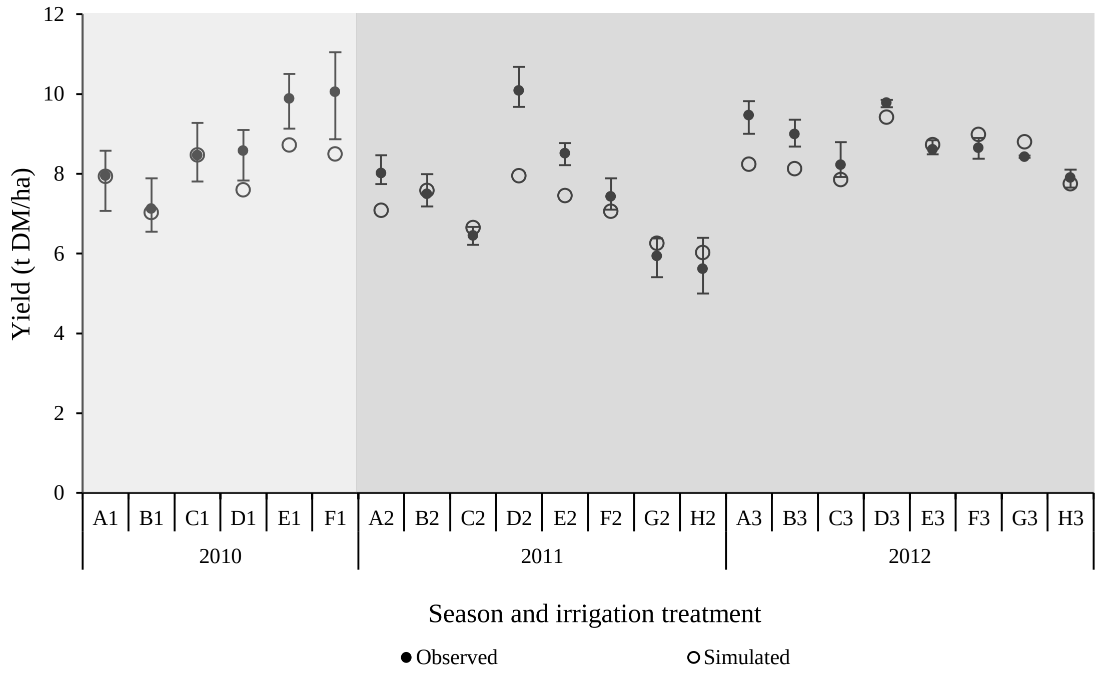

Figure 3 Histogram showing results the average variability in irrigation deviation (%) under a hose reel fitted with a boom and a linear move irrigation system.

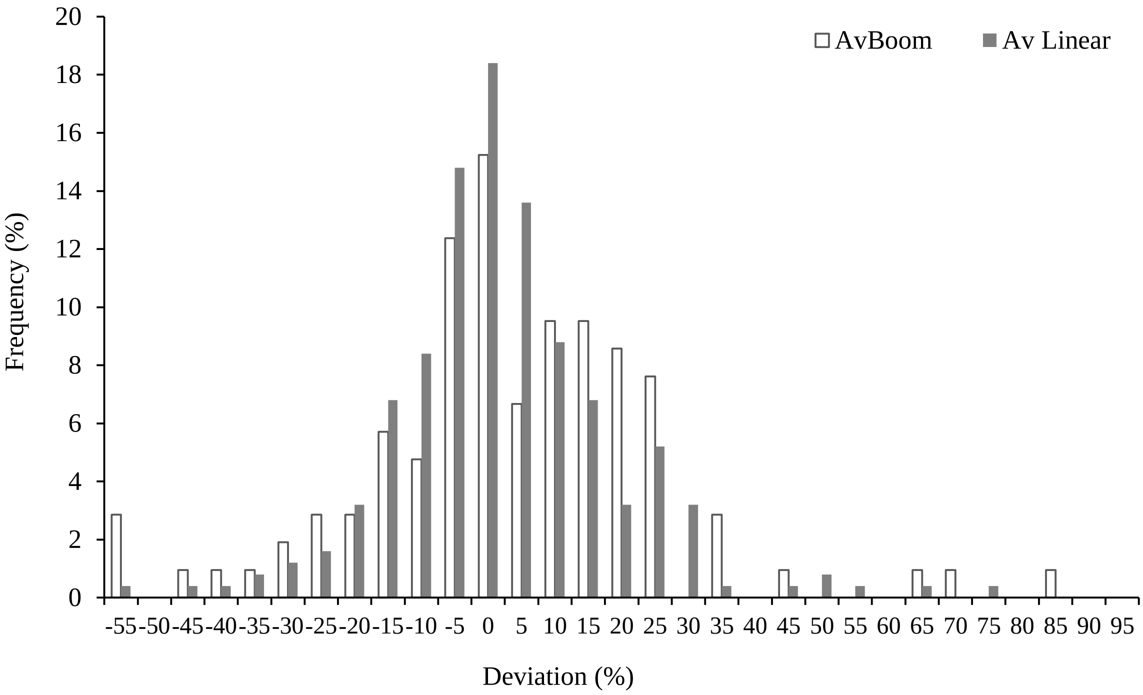

Figure 4a AquaCrop model simulated and observed brown onion (*cv. Arthur*) canopy cover (%) for each year (2010 to 2012) and treatment (A to H). Time line shows the days after planting (DAP).

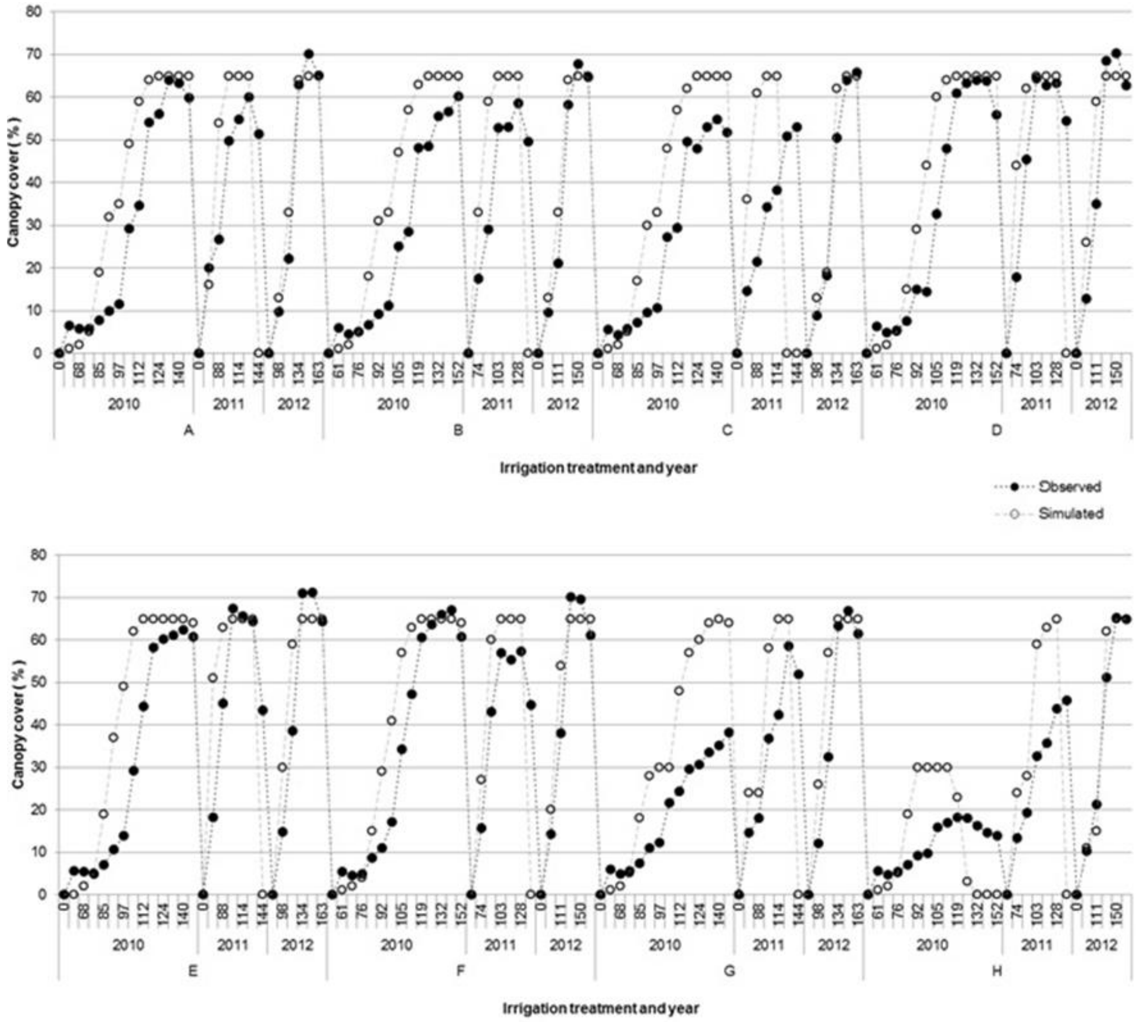

Figure 4b AquaCrop model simulated and observed brown onion (*cv. Arthur*) soil moisture deficit (SMD, mm) for each year (2010 to 2012) and treatment (A to H). Time line shows the days after planting (DAP).

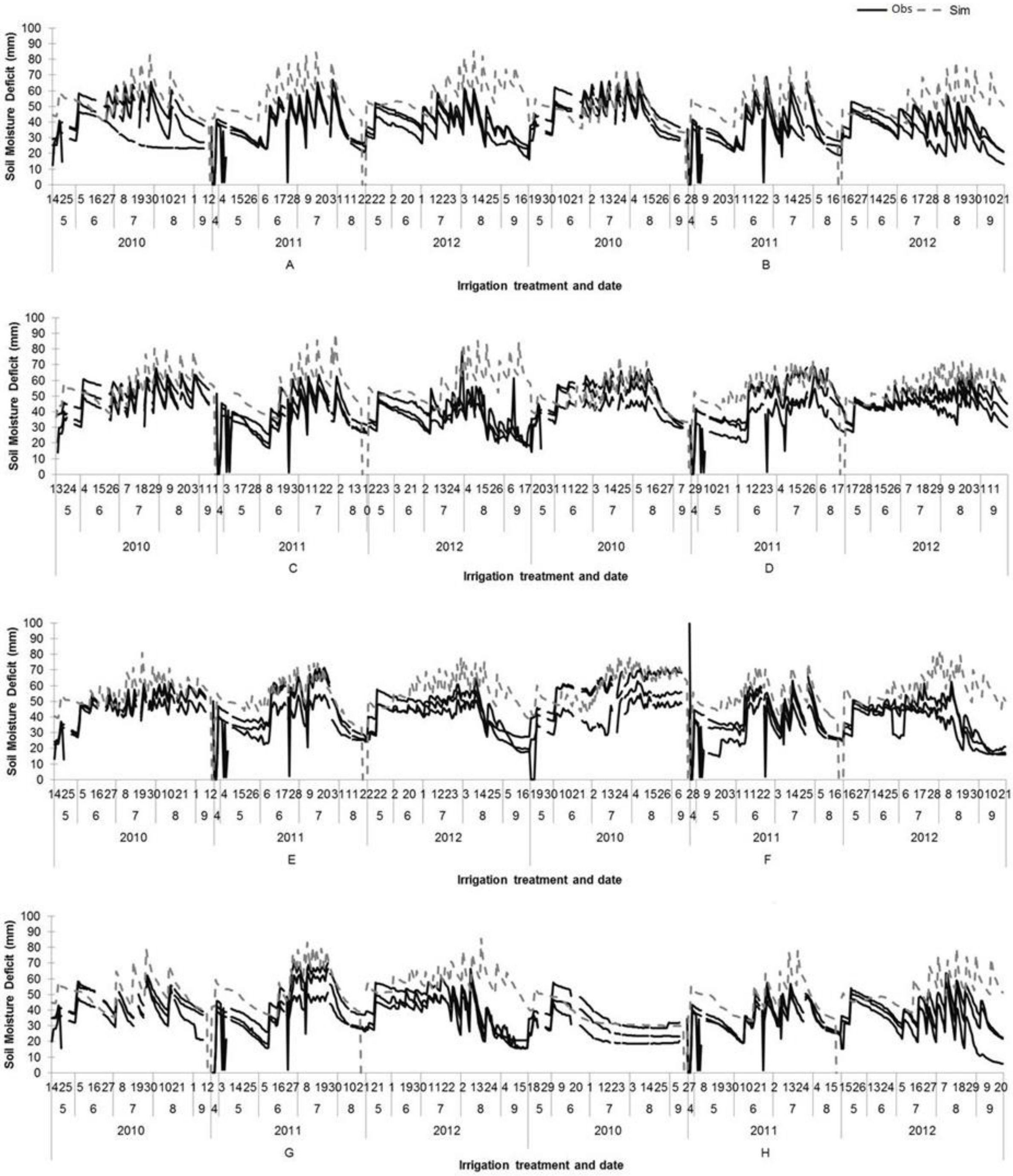

Figure 5 AquaCrop model simulated and observed onion yield (t/ha) for the validation period.

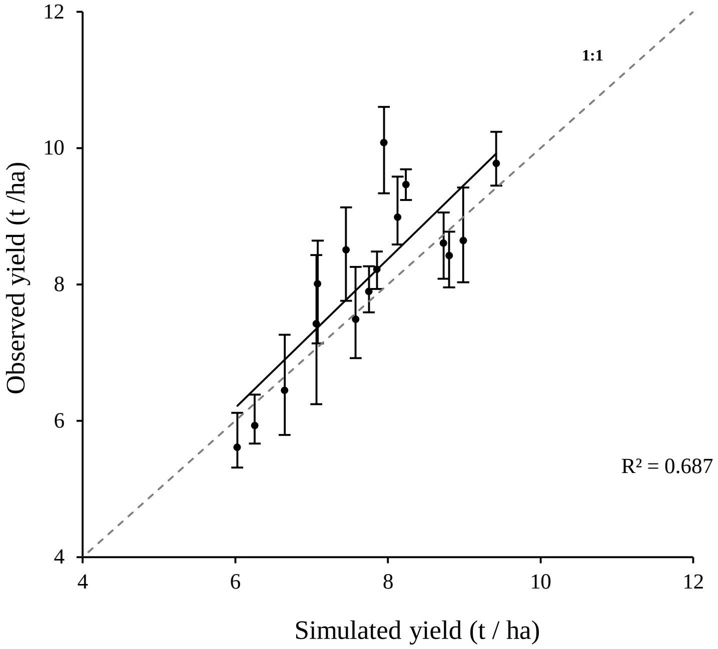

Figure 6 Box and whisker plot showing Aquacrop model simulated onion yield (t DM ha^{-1}) under 'uniform' irrigation and 'non-uniform' irrigation, using a hose reel with boom and a linear move application system, on a sandy and sandy loam soil, for each climate year (very wet, average wet, average, average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