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Implementing precision irrigation in a humid climate - recent experiences and on-going challenges

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Abstract

There is growing scientific interest in the potential role that precision irrigation (PI) can make towards improving crop productivity, and increasing water and energy efficiency in irrigated agriculture. Most progress has been made in arid and semi-arid climates for use in high value crop production where irrigation costs coupled with concerns regarding water scarcity have stimulated PI innovation and development. 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, help reduce the non-beneficial losses associated with irrigation (deep drainage, nitrate leaching) and provide farmers with evidence to demonstrate environmentally sustainable practices to processors and retailers. This paper reports on recent experiences in developing precision irrigation in UK field-scale agriculture, drawing on evidence from field research and modelling studies. By combining data from these sources, a critical evaluation focusing on selected technical, agronomic and engineering challenges that need to be overcome are described, including issues regarding PI scheduling, and the delineation of irrigation management zones to ensure compatibility with existing methods of overhead irrigation. The findings have relevance to other countries where irrigation is supplemental and where precision agriculture is gaining popularity.

Keywords: Electrical conductivity; precision agriculture; variable rate irrigation; irrigation uniformity; soil mapping; soil variability.

1. Introduction

Precision farming research and development has demonstrated how significant benefits can be obtained by the variable-rate application of seeds, fertilizers and pesticides. As a result, the concept of precision agriculture (PA) has gained widespread acceptance; it is conceptualized as a system approach, where low input, high efficiency sustainable agriculture are the primary goals (Zhang *et al.*, 2002). PA is also been promoted within the context of achieving the sustainable intensification of agriculture. There is now considerable interest worldwide in seeing if equivalent benefits of PA can be obtained from precision irrigation (PI), particularly in arid climates where water use is high, and where water scarcity is becoming a major constraint to production. But PI in temperate and humid climates, such as northern Europe, where cropping is rotational, water use is relatively low and irrigation schedules have to cope with uncertain and unpredictable rainfall, raises many new issues (Knox *et al.*, 2013). Despite widespread international use of the term, PI, as a scientific concept, is still very much in its infancy (Smith and Baillie, 2009). In industry, the term PI is often used to refer to optimal management of micro (drip or trickle) irrigation where precise volumes of water are applied directly into the root zone. Other researchers often refer to variable rate irrigation (VRI) under centre pivots as being the dominant form of PI.

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

The scale, type of production and method of irrigation are all critically important. This paper discusses the opportunities and challenges of developing PI on mobile hose-reel boom systems for vegetable irrigation in a humid environment generally, and then links these to observed measurements and system modeling for a representative field site. Here we attempt to provide a critical evaluation of the key technical, agronomic and engineering challenges that still need to be addressed, including the concept of irrigation management zones and how these should be defined to be compatible with existing methods of overhead irrigation. The key questions therefore raised in this paper include, (i) are the potential benefits of PI significant, (ii) at what scale does variable rate application need to be developed, (iii) can mobile hose-reel boom systems apply variable rate irrigation at these scales, and, (iv) do the additional costs justify investment in PI.

The paper first presents a brief overview of UK vegetable production to provide context for implementing PI. It then considers some fundamental differences between conventional and precision irrigation and the links with irrigation scheduling, since this is an important determinant in deciding how PI could be managed. Field data are then used to illustrate some of the challenges in deriving and delineating irrigation management zones (IMZ) for PI; finally, a broader discussion of the remaining agronomic and engineering challenges and concluding comments is provided.

1.1 Vegetable production in England

Water for agriculture is becoming increasingly scarce, even in humid countries. In England, irrigation accounts for typically less than 1% of total freshwater withdrawal. However, irrigation is a consumptive water use concentrated in the driest areas and driest months when water resources are most constrained (Knox *et al.*, 2010). King *et al* (2005) conducted a baseline assessment of agricultural water use in England and Wales and estimated total on-farm water abstraction was in excess of 300 $Mm^3\ y^{-1}$, with approximately 60% used for irrigation of outdoor field-scale agricultural and horticultural crops (128 $Mm^3\ y^{-1}$) most notably potatoes and vegetables.

Despite summer rainfall and a humid environment, water resources are fully committed particularly in the summer months in many catchments across southern and eastern England. About half of all agricultural and horticultural holdings are in catchments defined as either having ‘no (more) water available’ or are already ‘over- licensed’. Nearly a fifth are in ‘over-abstracted’ catchments. Therefore, in water stressed catchments, where irrigation water demand exceeds available surface or groundwater water supplies, reducing the irrigation water use through improved management and advanced irrigation technologies would mean that water resources could be released to sustain environmental flows or support other uses (Hess *et al*., 2010). Growers also have to demonstrate efficient and sustainable use of water to renew time-limited abstraction licenses, and increasingly, to comply with supermarket sustainability protocols (Knox *et al*., 2012). Collectively, these are important drivers for promoting the uptake of advanced or PI technologies, assuming of course that the financial benefits justify the investment.

In dry summers, agricultural irrigation is the first sector targeted for abstraction restriction. A restriction on water supply to growers producing high quality vegetables for supermarkets can be a critical business risk. Failure to supply the contracted quantity and/or (usually more importantly) to meet the contracted quality standards can lead to large penalties, price discounting or, in worst cases, crop rejection and loss of contract (Monaghan *et al*., 2013). In some instances buyers will not award a contract to a grower unless they can demonstrate access to adequate and reliable water resources. Weather variability, and an expected increase in drought frequency associated with climate change, is encouraging an increasing number of UK growers to invest in water storage reservoirs, despite the large capital cost. Even so, there are strong pressures to reduce water use, not least to allow irrigation of a larger area from the same water resource.

As well as assuring water resources, it is necessary to apply the water efficiently. Relatively few UK growers use trickle (drip) irrigation due to cost and practical issues (Knox and Weatherhead, 2005) and there are very few centre pivots and linear move systems in use, mainly due to small field sizes and cropping mixes. Most UK irrigated crops are grown in rotations with non-irrigated crops, and mobile systems are therefore preferred. Hose reels, fitted with either rain-guns or booms are used on more than 86% of field vegetables irrigated area in the UK (Weatherhead, 2007). They are popular not only for their relatively low capital cost (Morris *et al.*, 2013) but also because they provide the flexibility required for the rotational cropping patterns and for the supplemental irrigation which is typical in humid climate. High energy consumption and the relatively poor uniformity, especially in windy conditions, are notable drawbacks (Weatherhead, 2007); the issue of wind on overhead irrigation uniformity creates additional challenges for PI implantation. Within this context, the authors, working with industry colleagues, are assessing the potential for precision irrigation techniques, using hose-reel boom irrigators in the UK, and the trade-offs against conventional or traditional irrigation methods.

1.2 Traditional versus precision irrigation

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

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

2. Benefits of precision irrigation in a humid climate

The combination of mobile irrigators with current approaches to scheduling mean that the whole field block is typically irrigated with the same scheduled depth of water. If soils are uniform, then uniform irrigation across the block to maintain optimum soil water conditions should maximise both yield and quality. However, soils are naturally variable, often over short distances within an irrigated block. Where there are known differences in soil available water capacity (AWC) within a field, it is typical farm practice to schedule the irrigation according to the parts of the field with the lowest AWC in order to ensure that no part of the field is under-irrigated. This is because penalties from under-irrigation are generally perceived by growers to be higher than those associated with over-irrigation. Where growers use in-situ soil moisture sensors to schedule their irrigation, it is common practice to locate these in the parts of the field with lowest AWC and greatest risk of droughtiness (Peters *et al.*, 2013). This approach tends to increase the irrigation frequency and lead to more water being applied than necessary to those parts of the block with higher AWC. There is therefore potential to reduce both water and energy use, increase water use efficiency, and reduce leaching of nutrients by using PI to vary irrigation application within a block in response to known spatial differences in soil AWC.

In this study we considered the potential savings and benefits from PI for a potato crop grown in England for the fresh pre-pack retail sector (supermarket). Potato cultivation accounts for 43% of the total irrigated area and 54% of irrigation water use in England and Wales (Defra, 2011). Potatoes are grown in geographically diverse locations across England in a range of soil types from sand to clay, although the majority of potato production is on loamy soils. In the wetter parts of the country they can be grown without irrigation, however supplementary irrigation is used in most regions and most years to ensure crop yield and premium quality (Daccache *et al.*, 2011).

Three agroclimatic locations were selected to reflect the main potato growing regions in England – Silsoe, Bedfordshire (52.01° N; 0.42° W), Wattisham, Suffolk (52.12° N; 0.93° W) and Shawbury, Shropshire (52.47 °N; 2.39 °W) – and three loam soils reflecting high, medium and low AWC, respectively (Table 1). For each soil and climate combination, the seasonal irrigation water requirements (depths applied), water losses (sum of runoff and percolation) and soil moisture deficit (SMD) at harvest were estimated using the WaSim daily soil water balance model (Hess and Counsell, 2000) for the period 1986 to 2011. The weather of each year was characterised by the maximum potential SMD (PSMD_{max}) which has been shown to be a useful agroclimatic indicator that is well correlated with irrigation need (Knox *et al.,* 1997). A high PSMD_{max} reflects a year with low summer rainfall and high irrigation need. Irrigation was scheduled using typical irrigation schedules used by potato growers in England. Irrigation of potatoes grown for the pre-packed market in England is as much for quality as yield. Dry soil conditions following tuber initiation increases the risk of common scab (*Streptomyces scabies*), therefore an irrigation schedule was applied to maintain low soil water deficits for scab control (Lapwood *et al.*, 1970), with larger deficits allowed thereafter according to AWC (Table 2).

Seasonal irrigation need is presented in Table 3 for three years selected from each station to represent dry (PSMD_{max} with 10% probability of exceedance), average (50%) and wet (90%) years. These represent the water balance of each soil type under differential irrigation, that is, irrigation of each soil is scheduled according to its AWC. Across the three stations and 26 years, the irrigation requirements of the high AWC soil were 11% less than that of the low AWC soil.

The WaSim model was re-run for each year, assuming that medium and high AWC soils were irrigated at the times and with the amounts scheduled for the low AWC soil. These represent farmers' typical practice in a block with mixed soils, where irrigation is scheduled according to the soils with the lowest AWC. By comparing irrigation applied, water losses and final SMD with the corresponding values for differential irrigation, the potential water saving benefits of PI can be estimated. Table 4 shows that by scheduling the irrigation of the block according the low AWC, on average the medium and high AWC soils are over-irrigated by 18 mm and 22 mm; the additional water losses are 2 mm and 8 mm and the SMD at harvest is reduced by 16 mm and 17 mm, respectively. A lower SMD at harvest means that the soil will return to field capacity earlier in the autumn and drainage will start earlier on the over-irrigated parts of the field. There was no significant difference between the weather stations and no correlation with the year's weather (as expressed by the agroclimatic index, $\mathrm{PSMD}_{\mathrm{max}}$).

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

3. Exploratory case study

3.1 Site description and EMI soil mapping

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

3.2 Mapping available water capacity

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

Sensitivity analysis using the variance-based method was then used to further investigate the influence of each soil parameter on the measured ECa values. The variance-based method (Sobol, 1993) was chosen because it is considered the simplest and most effective method (Saltelli, 2002). The variance of the conditional mean (of the input variable of interest) was used as an indicator of how strong the influence of a certain parameter was on model variability. The results showed that the ECa values for this study site were most affected by organic matter content (41% of total variance contribution), followed by silt content (17%) and bulk density (12%). However, the complex interaction between soil variables represented around 20% of the total observed ECa variance. Soil moisture content at field capacity (FC) and permanent wilting point (PWP) were then obtained by using the soil texture fineness index (Waine *et al.*, 2000) to identify the location of soil samples on the abscissa of texture-moisture graph (Figure 2). The difference between the FC and PWP curves can be used to determine the AWC of each soil sample.

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

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

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

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

3.3 Using geo-statistical methods to optimize Irrigation Management Zones (IMZ)

The method of classification used and the range in AWC values determines the number, size and spatial distribution of IMZ. Various techniques have previously been developed to delineate these, with most often based on observed differences in soil (Oliveira *et al.*, 2003). Figure 3 shows, for example, how the classification method and number of derived classes can strongly influence IMZ delineation. For our field site, the AWC data were classified into 7 and then 3 classes, using two contrasting approaches, the equal interval method and natural (Jenks') break method (Figure 4). The Jenks' natural break classification determines the best arrangement of values into classes by iteratively comparing sums of the squared difference between observed values within each class and the class means. The "best" classification identifies breaks in the ordered distribution of values that minimizes the ‘within-class’ sum of squared differences. The natural break classification method therefore aims to minimize the variance within the group and maximize the difference between classes which is useful when considering AWC variability across an IMZ.

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

On the assumption that soil and crop water needs are similar across a field, a non-uniform water application will result in over and under–irrigation in the same plot with negative consequences on yield, quality, water and nutrient use efficiency. For that reason, overhead irrigation systems are designed to provide adequate overlapping from sprinklers to deliver the highest uniformity of water application. Any change in operation for a single sprinkler directly impacts on the wetted area and hence the depth of water applied under adjacent sprinklers. With hose-reel boom irrigators, applying variable irrigation at the sub-metre level is technically unfeasible given the short distance between individual sprinklers (2.5 to 4 m) and the need for overlap to achieve high uniformity. Hence, the raw AWC data must be aggregated into larger contiguous zones. These need to be large enough to be managed separately, yet small enough to minimize the soil AWC variability within them.

To evaluate this issue, the AWC data (Figure 3) were clustered using 3m^2, 6m^2 and 9m^2 pixel aggregations and classified into three IMZs using the Jenks' natural break method (Figure 5). The purpose of this was to analyse the impact of different management scales for delineating IMZs on field and water application variability. The range in AWC variation within each IMZ regardless of cluster scale is very similar in each IMZ. This is because extreme values are distributed across the field and within each IMZ. By taking the lower and upper quartiles, the differences become much more apparent across the three different zones. For example, at the 3m^2 scale, IMZ zone 1 appears to have the highest degree of variability. This is due to the large variability within a small area, which disappears when 6m^2 and 9 m^2 scales are used. The difference between 6m^2 and 9m^2 scale appears negligible (Figure 5).

3.4 Developing VRI on a mobile hose-reel boom

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

VRI can be achieved by fitting each sprinkler or nozzle with a remotely controlled on-off automatic valve. Fortunately this technology is already well developed for the golf industry, where individual sprinklers are operated sequentially along fairways and around greens. The relative duration of the on-off cycles will determine the depth of water applied. On-off control is preferred to trying to vary the pressure and flow rate, since that would also change drop sizes and throw and hence overlap.

However, this setup still imposes various limitations on PI possibilities. The sequential irrigation of strips around the field requires that irrigation can only occur on the dates determined by the schedule for the lightest (lowest moisture retentive) soils. The throw of each sprinkler limits the minimum scale at which VRI can be physically applied. The overlap between sprinklers, which normally improves uniformity, makes it impossible to generate sharp changes in depth applied at boundaries between irrigation management zones or to stop irrigation across paths or for gaps in the crop. Some improvement can be achieved by using more sprinklers with smaller throws, but this raises the instantaneous application rate near to the boom leading to the risk of ponding and runoff, particularly on sloping fields.

A further issue is caused by the drive mechanism on the hose reels. Most UK systems use through-flow turbines to drive the reel, taking some of the energy from the water before it travels along the hose to the boom. However, this imposes a minimum flow rate before the turbine stalls and the pull-in ceases. Typically no more than half the nozzles could be closed simultaneously. Furthermore, a change in flow will typically alter the pull-in speed. The reel therefore needs to be fitted with a sophisticated speed controller, or the change taken into consideration by the control system. Using a piston drive, which bleeds off a portion of the water and then discharges it, would waste water, while a switch to separate motor-driven reel operation, as used in some other countries (e.g. Canada) would add costs.

In this study, a commercially available boom (Briggs) was adapted by the addition of wirelessly controlled on-off solenoid valves. This consists of a four wheeled steel chassis fitted with 13 sprinklers (Nelson R2000WF) each 2.5 m apart and fixed 1.5 m above the ground level. Each sprinkler can be controlled by an on-off solenoid valve, controlled centrally via wireless radio links.

3.5 Hose-reel boom simulation

It is clearly impractical to test all the possible settings under full scale field trials, particularly given the uncontrollable element of wind. A boom simulation model was therefore developed to aid optimization. This uses ballistic approach on a single drop to predict the wetting patterns under still or windy conditions (Carrion *et al.*, 2000) and overlap wetting patterns based on the boom design and operational mode. The model is calibrated using the individual sprinkler water profiles (Nelson R3000) tested under 'no wind' conditions at different pressures (15, 25 and 35 m). Details on system design (including sprinkler spacing (2.75m), the individual sprinkler height (1.35m), hose length (300m), pipe size (110mm), pulling speed (15m/h), boom width (33m)) and land topography are all entered as inputs. These boom parameters were chosen to reflect typical operating boom settings used in field-scale horticultural cropping in the UK. Model outputs include the spatial distribution of water volume (depths) across the field when operating under either a uniform rate irrigation (URI) or variable rate irrigation (VRI) schedule.

In the example run presented here, the system was scheduled to apply 23 mm water over the entire field under URI. Under VRI, using the zones previously defined (Figure 5), at 3m^2, 6m^2 and 9m^2 grid pixel resolutions, the boom was programmed to try and apply the full (100%) irrigation capacity on zone 1 (low AWC), 50% across zone 2 (medium AWC) and 25% in zone 3 (high AWC). The resulting water application patterns are presented in Figure 6. The URI plot shows the non-uniformity inherent in the sprinkler arrangement, even with no wind. The VRI plots clearly show the differences in depths of water applied in each IMZ, as the boom tries to respond to the different target depths. The depths applied in each zone are compared in Figure 7 using a box and whisker plot to show the median, quartile and extreme values. With the zones defined at a 3m^2 grid resolution, the boom struggles to match the target schedule, with too little applied on zone 1 and too much on zone 2. With the larger zones, at 6m^2 resolution, the applications are closer, though still slightly under irrigating zone 1 and over irrigating zones 2 and 3. The performance is very similar with the 9m^2 resolution zones. These results show the inevitable problems due to sprinkler overlapping at the edges of the IMZ, and the resulting poor uniformity within each zone, although they are clearly an improvement over applying the full application (URI) where it is not needed.

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

4. Discussion and concluding remarks

At the outset, four questions were posed in this paper, namely (i) are the potential benefits of PI significant in a humid climate, (ii) at what scale does variable rate application need to be developed, (iii) can mobile hose-reel boom systems apply variable rate irrigation, and, (iv) whether the additional costs for PI justify the investment. The key findings for each are summarised below.

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

As shown in section 2, the potential benefits from PI for irrigated potatoes in England appear modest. The estimated water savings are around 20 mm/year on those parts of the field that would be over-irrigated by uniform irrigation (Table 4). PI has little impact on drainage during the growing season, which is mostly caused by unpredictable rainfall. In part, these results reflect the need to keep the SMD small during the scab-control period, irrespective of soil type. This is not necessarily the case for other high- value crops where scab control scheduling is not needed (for example, a shallow rooting salad crop). Further investigations on the potential benefits of PI are therefore needed to cover a broader range of crop types as these might show different responses. The simulation also assumed that evapotranspiration (ET) under irrigated conditions is the same irrespective of soil texture. In reality difference in soil texture may lead to differences in rooting depth or fertility such that plant growth and ET also differ.

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

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

4.3 Can mobile hose-reel boom systems apply variable rate irrigation?

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

4.4 Do the additional costs justify investment in PI?

The benefits of PI will of course be site and crop specific and depend on other factors such as the magnitude of soil variability within the field, climate conditions, method of irrigation, and cost of water (particularly if storage is required). The benefit to the grower in the reduced cost of water and energy is estimated to be typically less than £25 per hectare that is over-irrigated. Clearly the development and uptake of PI would need to be justified more in terms of the wider benefits to crop quality and reduced environmental impacts. Further work is required to assess these under real situations and to provide quantitative evidence to substantiate claims being made about the agronomic benefits of precision irrigation.

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Table 1 Soil characteristics of each of three AWC classes.

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

Table 2 Typical agronomic practices and irrigation scheduling of pre-pack main potato crop in the UK on low, medium and high AWC soils (MAFF, 1982).

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

Table 3 Modelled potato irrigation needs at the study sites in a dry, average and wet year at three locations in England on soils with low, medium and high available water capacity.

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

Table 4 Additional irrigation applied (mm/yr), increased losses (drainage and runoff) (mm/yr) and reduction in soil moisture deficit (SMD) (mm) at harvest resulting from scheduling all soils according to low AWC.

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

Figure 1 Spatial variation measured at the lettuce field site (Cambridge, 2012) using EMI technology. The location of soil sampling points are highlighted.

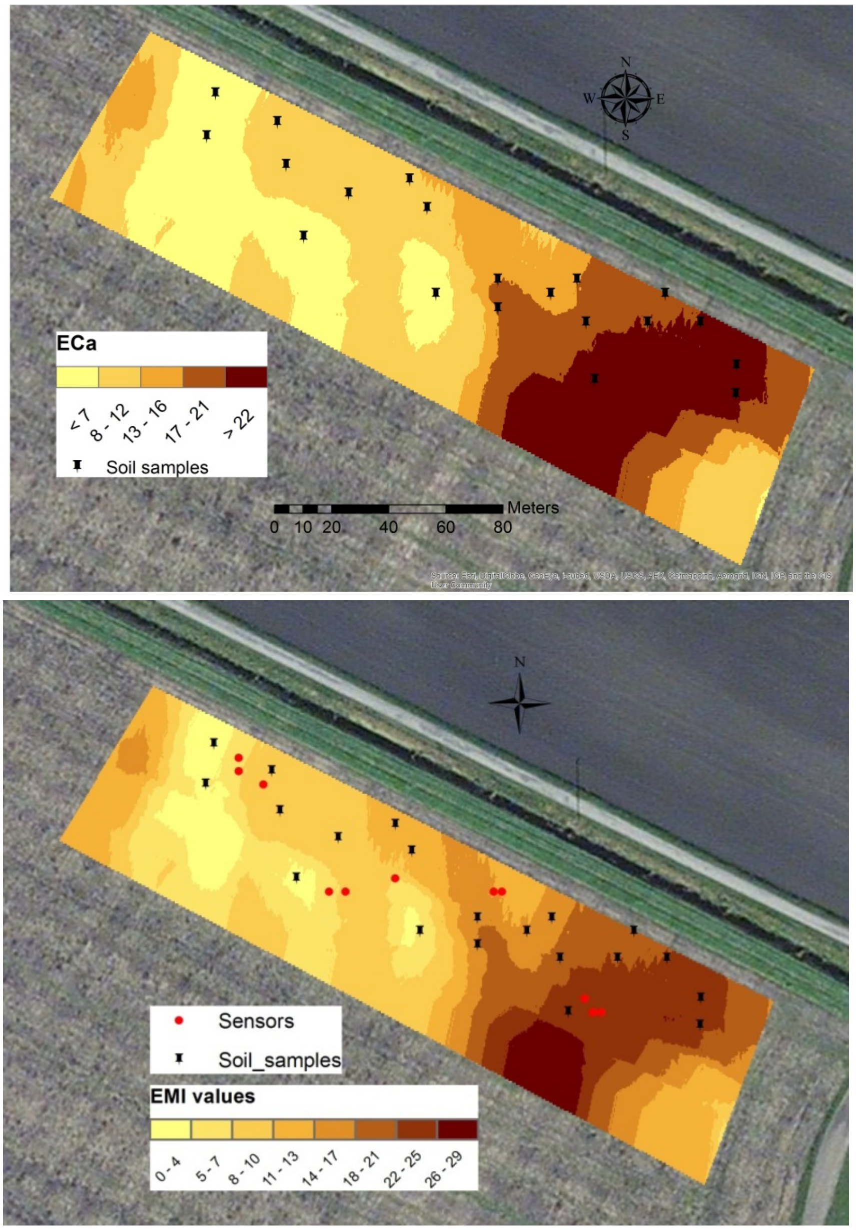


Figure 2 UK moisture release curve for typical soils (Waine *et al*., 2000).

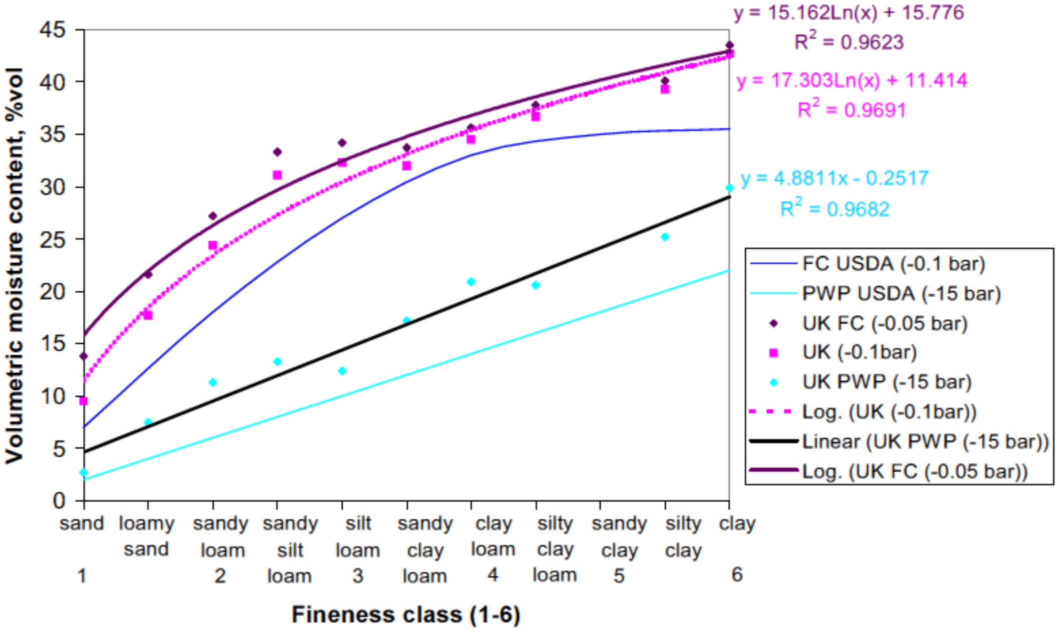
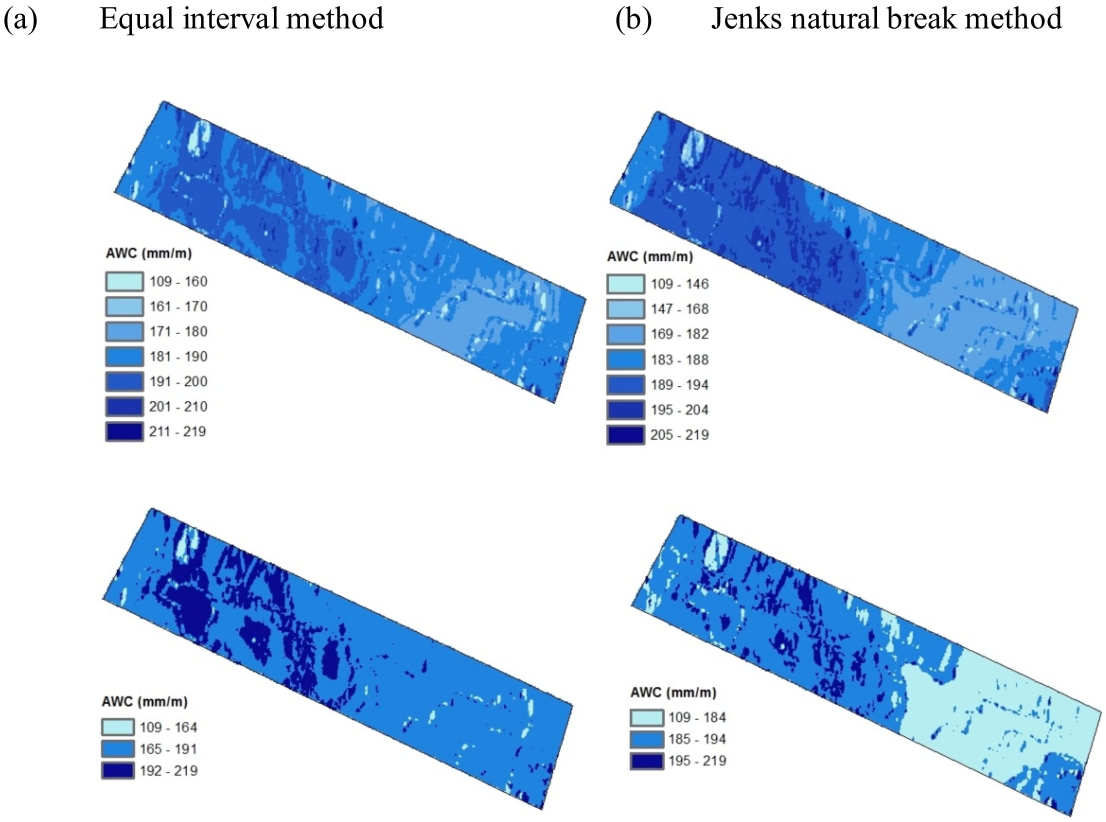
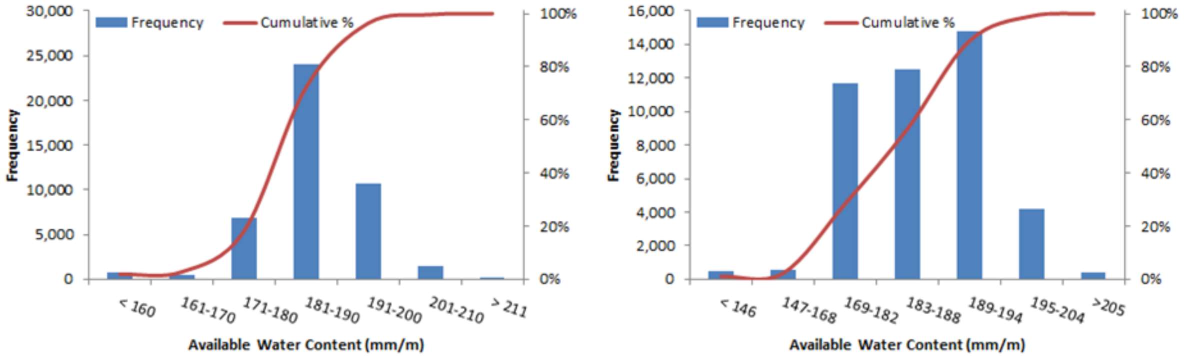


Figure 3 Maps showing spatial variation in AWC generated from the EMI data, classified into 7 and 3 classes using equal interval (a) and Jenks natural break (b) methods.


(a) Equal interval method

(b) Jenks natural break method

Figure 4 Frequency and cumulative percentage of AWC values within each interval using a) equal interval and b) natural break classification.


(c) Equal interval method

(d) Jenks natural break method

Figure 5 Irrigation management zones (IMZ) clustered at 3 m^2, 6 m^2 and 9m^2.

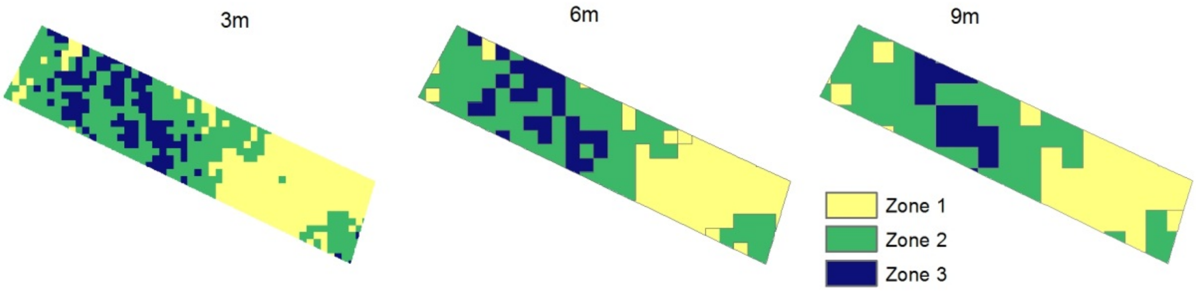


Figure 6 Spatial distribution of water applied at full uniform irrigation and VRI at 3m^2, 6m^2 and 9m^2 clustering resolution.

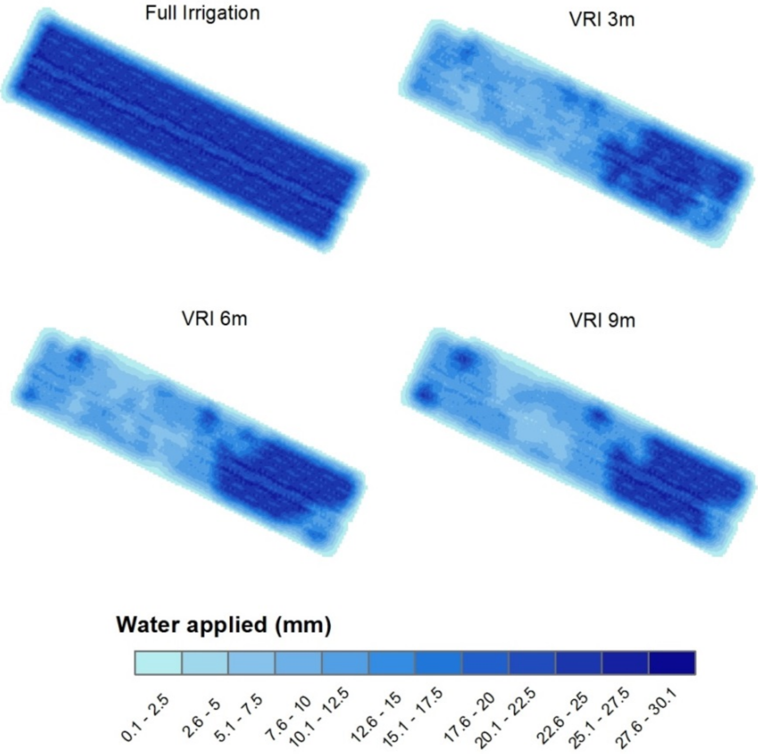
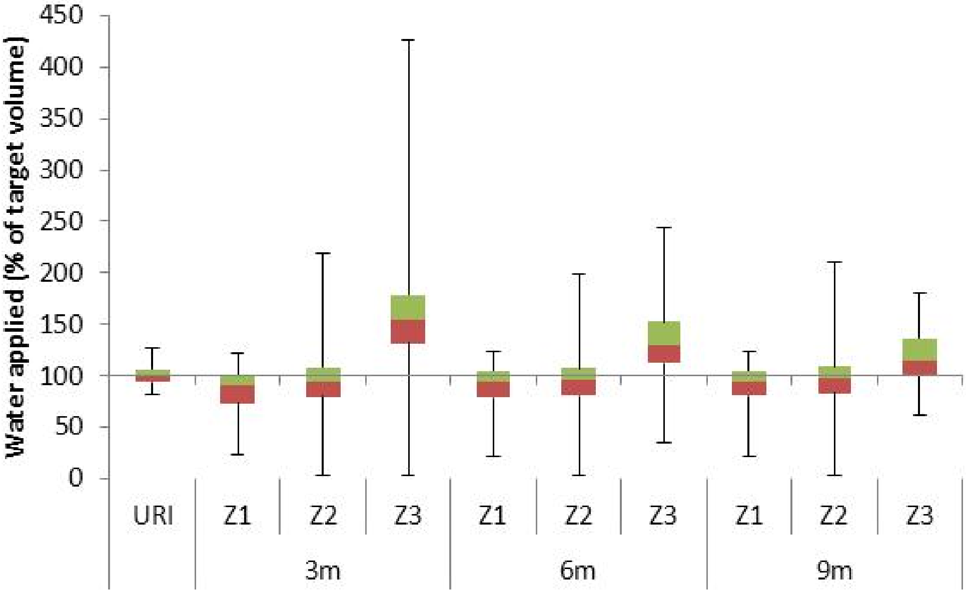


Figure 7 Simulated depths of water applied (mm) in each irrigation management zone under uniform (URI) and variable rate irrigation (VRI), with the zones defined at 3m, 6m and 9m scales. Depths are expressed as % of the target application in that zone (100%, 50% and 25% for Z1, Z2 and Z3, respectively). Boxes represent the median, upper and lower quartile depths while error bars show the minimum and maximum range.



Implementing precision irrigation in a humid climate - Recent experiences and on-going challenges

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