

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

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6 **Abstract**

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

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

25 **1. Introduction**

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

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

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

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

67 *1.1 Vegetable production in England*

68 Water for agriculture is becoming increasingly scarce, even in humid countries. In England,
69 irrigation accounts for typically less than 1% of total freshwater withdrawal. However,
70 irrigation is a consumptive water use concentrated in the driest areas and driest months when
71 water resources are most constrained (Knox *et al.*, 2010). King *et al* (2005) conducted a
72 baseline assessment of agricultural water use in England and Wales and estimated total on-
73 farm water abstraction was in excess of 300 Mm³ y⁻¹, with approximately 60% used for

74 irrigation of outdoor field-scale agricultural and horticultural crops ($128 \text{ Mm}^3 \text{ y}^{-1}$) most
75 notably potatoes and vegetables.

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

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

98 are strong pressures to reduce water use, not least to allow irrigation of a larger area from the
99 same water resource.

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

115 *1.2 Traditional versus precision irrigation*

116 Traditionally, irrigators have ignored soil and crop variability within an irrigated block and
117 attempted to apply water uniformly across the field. Therefore, unless the soil is also uniform,
118 this means that some parts of the field will be under- or over-irrigated. Under-irrigation
119 impacts on crop yield and quality which in high-value field-scale vegetable production is a
120 key driver for irrigation investment. Under-watering may also lead to increased nitrate
121 leaching after harvest due to inefficient uptake of nutrients during the growing season
122 (Groves and Bailey, 1997; Bailey and Groves, 1992). Over-watering is, by definition, a waste

123 of water, and therefore energy. However, by keeping parts of the block wetter than necessary
124 during the growing period, there is also an increased risk of drainage and leaching, either
125 from the irrigation itself, or from subsequent rainfall (Shepherd *et al.*, 1993). This is
126 particularly important in situations where the soil is kept close to field capacity in the spring
127 (e.g. for scab control on potatoes). In the extreme, over-irrigation can cause waterlogging,
128 with impacts on crop yield, quality and soil trafficability.

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

147 **2. Benefits of precision irrigation in a humid climate**

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

164 In this study we considered the potential savings and benefits from PI for a potato crop grown
165 in England for the fresh pre-pack retail sector (supermarket). Potato cultivation accounts for
166 43% of the total irrigated area and 54% of irrigation water use in England and Wales (Defra,
167 2011). Potatoes are grown in geographically diverse locations across England in a range of
168 soil types from sand to clay, although the majority of potato production is on loamy soils. In
169 the wetter parts of the country they can be grown without irrigation, however supplementary
170 irrigation is used in most regions and most years to ensure crop yield and premium quality
171 (Daccache *et al.*, 2011).

172 Three agroclimatic locations were selected to reflect the main potato growing regions in
173 England – Silsoe, Bedfordshire (52.01° N; 0.42° W), Wattisham, Suffolk (52.12° N; 0.93° W)
174 and Shawbury, Shropshire (52.47 °N; 2.39 °W) – and three loam soils reflecting high, medium
175 and low AWC, respectively (Table 1). For each soil and climate combination, the seasonal
176 irrigation water requirements (depths applied), water losses (sum of runoff and percolation)
177 and soil moisture deficit (SMD) at harvest were estimated using the WaSim daily soil water
178 balance model (Hess and Counsell, 2000) for the period 1986 to 2011. The weather of each
179 year was characterised by the maximum potential SMD (PSMD_{max}) which has been shown to
180 be a useful agroclimatic indicator that is well correlated with irrigation need (Knox *et al.*,
181 1997). A high PSMD_{max} reflects a year with low summer rainfall and high irrigation need.
182 Irrigation was scheduled using typical irrigation schedules used by potato growers in England.
183 Irrigation of potatoes grown for the pre-packed market in England is as much for quality as
184 yield. Dry soil conditions following tuber initiation increases the risk of common scab
185 (*Streptomyces scabies*), therefore an irrigation schedule was applied to maintain low soil
186 water deficits for scab control (Lapwood *et al.*, 1970), with larger deficits allowed thereafter
187 according to AWC (Table 2).

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

194 The WaSim model was re-run for each year, assuming that medium and high AWC soils were
195 irrigated at the times and with the amounts scheduled for the low AWC soil. These represent
196 farmers' typical practice in a block with mixed soils, where irrigation is scheduled according

197 to the soils with the lowest AWC. By comparing irrigation applied, water losses and final
198 SMD with the corresponding values for differential irrigation, the potential water saving
199 benefits of PI can be estimated. Table 4 shows that by scheduling the irrigation of the block
200 according the low AWC, on average the medium and high AWC soils are over-irrigated by
201 18 mm and 22 mm; the additional water losses are 2 mm and 8 mm and the SMD at harvest is
202 reduced by 16 mm and 17 mm, respectively. A lower SMD at harvest means that the soil will
203 return to field capacity earlier in the autumn and drainage will start earlier on the over-
204 irrigated parts of the field. There was no significant difference between the weather stations
205 and no correlation with the year's weather (as expressed by the agroclimatic index,
206 $PSMD_{max}$).

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

217 **3. Exploratory case study**

218 *3.1 Site description and EMI soil mapping*

219 Understanding spatial soil variability is therefore a crucial component for PI (Hedley *et al.*,
220 2009). The conventional approach, using soil survey and dense sampling would be the most

221 accurate but analysing a large number of samples is time consuming and a major financial and
222 resource constraint. An alternative approach is to infer soil AWC from soil properties that can
223 be determined from rapid, non-invasive and low-cost electro-magnetic induction (EMI)
224 scanning. As part of a broader study investigating PI in field-scale horticulture, a flat field on
225 a commercial farm in Cambridgeshire (52.47°N, 0.357°E, -2m asl) was chosen to illustrate
226 soil variability and to identify the technical challenges. In-field soil variability was assessed
227 using Geonics EM38 scanner carried by hand and fitted with high accuracy DGPS positioning
228 system. Such technology has been used by other researchers to identify soil variability at field
229 scale (e.g. Hedley *et al.* 2009, James *et al.* 2003) and to inform PI scheduling (Hedley *et al.*,
230 2011). The apparent electrical conductivity (ECa) point data measured by the EMI scanner
231 were interpolated to 1 metre grid to produce the soil (ECa) map (Figure 1). An ordinary
232 kriging method was chosen as it outperformed using RMSE (Root Mean Square Error) other
233 interpolation techniques (e.g. spline, natural neighbour). Similar findings were obtained by
234 Hedley *et al.* (2012) and Robinson and Metternicht (2006).

235 *3.2 Mapping available water capacity*

236 To highlight the challenges of using EMI technology to map soil variability, 20 soil samples
237 were randomly taken from the field for laboratory analysis for particle composition (texture),
238 bulk density and organic carbon content. In humid climates where rainfall exceeds the
239 evapotranspiration (ET), salt build-up is not usually a problem and hence organic matter
240 content, mineralogy, bulk density and soil moisture content are considered the most important
241 factors influencing the measured ECa values (Brevik and Fenton, 2002). Clay and silty clay
242 were the dominant soil textures in the field with an average clay content of 45% (ranging
243 between 37% and 53%) and a bulk density of 0.96 g cm⁻³ (ranging from 0.77 to 1.99 g.cm⁻³).
244 The high organic matter content (18% to 25%) typifies the organic rich fenland soil (drained
245 marshland) in that part of the country. Using linear regression analysis, the highest correlation

246 with the measured ECa at that site was observed with organic matter ($R^2 = 0.71$) and bulk
247 density ($R^2 = 0.65$) and to lower extent with sand ($R^2=0.48$) and clay ($R^2 = 0.39$) content. This
248 confirmed that the ECa values do not reflect the dominance of a single soil parameter but
249 rather a combination of different factors.

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

263 As with other soil parameters, a poor linear correlation was observed between the ECa values
264 and AWC. Therefore, it is reasonable to suspect that the relationship between ECa and AWC
265 is not linear. According to the scatter plot between these two variables, we can rule out
266 quadratic, cubic, or even a non-polynomial relationship between ECa and AWC. An
267 alternative method is to use the principle of model selection to choose among the various
268 possibilities. Gaussian process regression (GPR) is an even finer approach than this. Using
269 this method rather than assuming a pre-specified model (e.g. linear, quadratic) to be fitted to
270 the data, we can rigorously let the data ‘speak’ more clearly for itself. GPR is considered a

271 form of supervised learning, but the training data are harnessed in an ingenious way. In other
 272 words a Gaussian process model is a data interpolation tool which can be used to infer the
 273 relationship between input variable(s) and the corresponding output. The main assumption
 274 required to use GPR is that the underlying function of interest is continuous (see Oakley and
 275 O'Hagan, 2004). The properties of this method are that (i) it will predict the model output at
 276 any of training data points with zero variance, (ii) that the predictions of the model output at
 277 other points will have non-zero variance, reflecting realistic uncertainty, and (iii) given
 278 sufficient training data it should be able to predict the model output to any desired level of
 279 accuracy. Therefore, GPR is a more suitable tool to model the non-linear relationship between
 280 AWC and ECa. In order to examine the accuracy of the fitted model in practice, we used the
 281 predicted residual sums of squares statistic which is a form of cross-validation and can be
 282 considered as a measure of predictive power. To compute this statistic after fitting the model
 283 of interest to the data, we remove each observation in turn from the whole data set and the
 284 model is refitted using the remaining observations. The out-of-sample predicted value is
 285 calculated for the omitted observation in each case, and the statistic is calculated as the sum of
 286 the squares of all the resulting prediction errors as follows:

$$287 \quad PS = \sum_{i=1}^n (AWC_i - A\hat{W}C_i)^2$$

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

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

308 *3.3 Using geo-statistical methods to optimize Irrigation Management Zones (IMZ)*

309 The method of classification used and the range in AWC values determines the number, size
310 and spatial distribution of IMZ. Various techniques have previously been developed to
311 delineate these, with most often based on observed differences in soil (Oliveira *et al.*, 2003).
312 Figure 3 shows, for example, how the classification method and number of derived classes
313 can strongly influence IMZ delineation. For our field site, the AWC data were classified into
314 7 and then 3 classes, using two contrasting approaches, the equal interval method and natural
315 (Jenks') break method (Figure 4). The Jenks' natural break classification determines the best
316 arrangement of values into classes by iteratively comparing sums of the squared difference
317 between observed values within each class and the class means. The "best" classification
318 identifies breaks in the ordered distribution of values that minimizes the 'within-class' sum of
319 squared differences. The natural break classification method therefore aims to minimize the

320 variance within the group and maximize the difference between classes which is useful when
321 considering AWC variability across an IMZ.

322 With equal breaks, over three quarters (80%) of the field is classified as one AWC class (180
323 to 190 mm/m) (Figure 4). In contrast, the Jenks' natural break classification identifies three
324 AWC classes (ranging between 169 and 194 mm/m) each with a similar frequency (Figure 4).
325 When the number of AWC classes is reduced from 7 to 3, three IMZ covering 55%, 33% and
326 10% of the field exist. However, when the equal breaks method is used two IMZ's covering
327 97% of the field result, which mask much of the variability in AWC (Figure 4. In reality, for
328 this field, the range in AWC is actually relatively small, probably reflecting a deliberate
329 decision by the farmer to grow high-value lettuce in a field with limited soil heterogeneity so
330 as to minimise impacts on crop development, yield and quality. However, even with a small
331 range in AWC, the spatial aggregation of IMZs is important, as their shape and area need to
332 be compatible with the method of irrigation.

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

344 To evaluate this issue, the AWC data (Figure 3) were clustered using 3m², 6m² and 9m² pixel
345 aggregations and classified into three IMZs using the Jenks' natural break method (Figure 5).
346 The purpose of this was to analyse the impact of different management scales for delineating
347 IMZs on field and water application variability. The range in AWC variation within each IMZ
348 regardless of cluster scale is very similar in each IMZ. This is because extreme values are
349 distributed across the field and within each IMZ. By taking the lower and upper quartiles, the
350 differences become much more apparent across the three different zones. For example, at the
351 3m² scale, IMZ zone 1 appears to have the highest degree of variability. This is due to the
352 large variability within a small area, which disappears when 6m² and 9 m² scales are used.
353 The difference between 6m² and 9m² scale appears negligible (Figure 5).

354 *3.4 Developing VRI on a mobile hose-reel boom*

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

366 VRI can be achieved by fitting each sprinkler or nozzle with a remotely controlled on-off
367 automatic valve. Fortunately this technology is already well developed for the golf industry,
368 where individual sprinklers are operated sequentially along fairways and around greens. The

369 relative duration of the on-off cycles will determine the depth of water applied. On-off control
370 is preferred to trying to vary the pressure and flow rate, since that would also change drop
371 sizes and throw and hence overlap.

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

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

390 In this study, a commercially available boom (Briggs) was adapted by the addition of
391 wirelessly controlled on-off solenoid valves. This consists of a four wheeled steel chassis
392 fitted with 13 sprinklers (Nelson R2000WF) each 2.5 m apart and fixed 1.5 m above the

393 ground level. Each sprinkler can be controlled by an on-off solenoid valve, controlled
394 centrally via wireless radio links.

395 *3.5 Hose-reel boom simulation*

396 It is clearly impractical to test all the possible settings under full scale field trials, particularly
397 given the uncontrollable element of wind. A boom simulation model was therefore developed
398 to aid optimization. This uses ballistic approach on a single drop to predict the wetting
399 patterns under still or windy conditions (Carrion *et al.*, 2000) and overlap wetting patterns
400 based on the boom design and operational mode. The model is calibrated using the individual
401 sprinkler water profiles (Nelson R3000) tested under ‘no wind’ conditions at different
402 pressures (15, 25 and 35 m). Details on system design (including sprinkler spacing (2.75m),
403 the individual sprinkler height (1.35m), hose length (300m), pipe size (110mm), pulling speed
404 (15m/h), boom width (33m)) and land topography are all entered as inputs. These boom
405 parameters were chosen to reflect typical operating boom settings used in field-scale
406 horticultural cropping in the UK. Model outputs include the spatial distribution of water
407 volume (depths) across the field when operating under either a uniform rate irrigation (URI)
408 or variable rate irrigation (VRI) schedule.

409 In the example run presented here, the system was scheduled to apply 23 mm water over the
410 entire field under URI. Under VRI, using the zones previously defined (Figure 5), at 3m², 6m²
411 and 9m² grid pixel resolutions, the boom was programmed to try and apply the full (100%)
412 irrigation capacity on zone 1 (low AWC), 50% across zone 2 (medium AWC) and 25% in
413 zone 3 (high AWC). The resulting water application patterns are presented in Figure 6. The
414 URI plot shows the non-uniformity inherent in the sprinkler arrangement, even with no wind.
415 The VRI plots clearly show the differences in depths of water applied in each IMZ, as the
416 boom tries to respond to the different target depths. The depths applied in each zone are
417 compared in Figure 7 using a box and whisker plot to show the median, quartile and extreme

418 values. With the zones defined at a 3m² grid resolution, the boom struggles to match the target
419 schedule, with too little applied on zone 1 and too much on zone 2. With the larger zones, at
420 6m² resolution, the applications are closer, though still slightly under irrigating zone 1 and
421 over irrigating zones 2 and 3. The performance is very similar with the 9m² resolution zones.
422 These results show the inevitable problems due to sprinkler overlapping at the edges of the
423 IMZ, and the resulting poor uniformity within each zone, although they are clearly an
424 improvement over applying the full application (URI) where it is not needed.

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

431 **4. Discussion and concluding remarks**

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

437 *4.1 Are the potential benefits of PI significant in a humid climate?*

438 As shown in section 2, the potential benefits from PI for irrigated potatoes in England appear
439 modest. The estimated water savings are around 20 mm/year on those parts of the field that
440 would be over-irrigated by uniform irrigation (Table 4). PI has little impact on drainage
441 during the growing season, which is mostly caused by unpredictable rainfall. In part, these

442 results reflect the need to keep the SMD small during the scab-control period, irrespective of
443 soil type. This is not necessarily the case for other high- value crops where scab control
444 scheduling is not needed (for example, a shallow rooting salad crop). Further investigations
445 on the potential benefits of PI are therefore needed to cover a broader range of crop types as
446 these might show different responses. The simulation also assumed that evapotranspiration
447 (ET) under irrigated conditions is the same irrespective of soil texture. In reality difference in
448 soil texture may lead to differences in rooting depth or fertility such that plant growth and ET
449 also differ.

450 *4.2 At what scale does variable rate application need to be developed?*

451 This study highlighted some challenges in mapping spatial variability in AWC from EMI data
452 and delineating IMZ that are compatible with the spatial scale inherent in the overhead
453 application systems used on vegetable crops in the UK. Many issues identified here are
454 common to more arid climates. In particular, IMZs need to be large enough to be managed as
455 discrete units, yet small enough to minimise soil AWC variability within them. The risk in
456 defining zones that are too small to cope with overlapping sprinklers, resulting in high
457 variation in the scheduled application depth, and ‘edge effects’ of many small units located
458 within a larger homogenous IMZ have also been demonstrated. Rather than varying the
459 application rate in each IMZ, Smith *et al* (2010) suggest an alternative would be to modify the
460 irrigation interval or timing. In the UK farmers generally consider the crop risks associated
461 with under-irrigation to be much higher than over-irrigation. At present, the relatively low
462 marginal cost of water applied would be sufficient to discourage growers to save water via PI;
463 other indirect benefits such as reduced variability in crop quality and reduced environmental
464 impact would more likely convince growers of the benefits of PI in a humid climate. Finally,
465 irrigation schedules are constrained by the operating characteristics of hose-reel boom system,
466 with the whole run being irrigated on a specific day. This can limit the benefits from PI, since

467 schedules cannot be optimised for each IMZ without further development to incorporate
468 feedback from in-situ soil moisture monitoring. The number and location of soil moisture
469 sensors needed to monitor the temporal variation in soil moisture content, and hence
470 determine PI schedules, would also depend on the number of the IMZ needed for each field.

471 *4.3 Can mobile hose-reel boom systems apply variable rate irrigation?*

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

479 *4.4 Do the additional costs justify investment in PI?*

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

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587

588

589 **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

590

591 **Table 2** Typical agronomic practices and irrigation scheduling of pre-pack main potato crop
592 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

593

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

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

596

597 **Table 4** Additional irrigation applied (mm/yr), increased losses (drainage and runoff) (mm/yr)
 598 and reduction in soil moisture deficit (SMD) (mm) at harvest resulting from scheduling all
 599 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

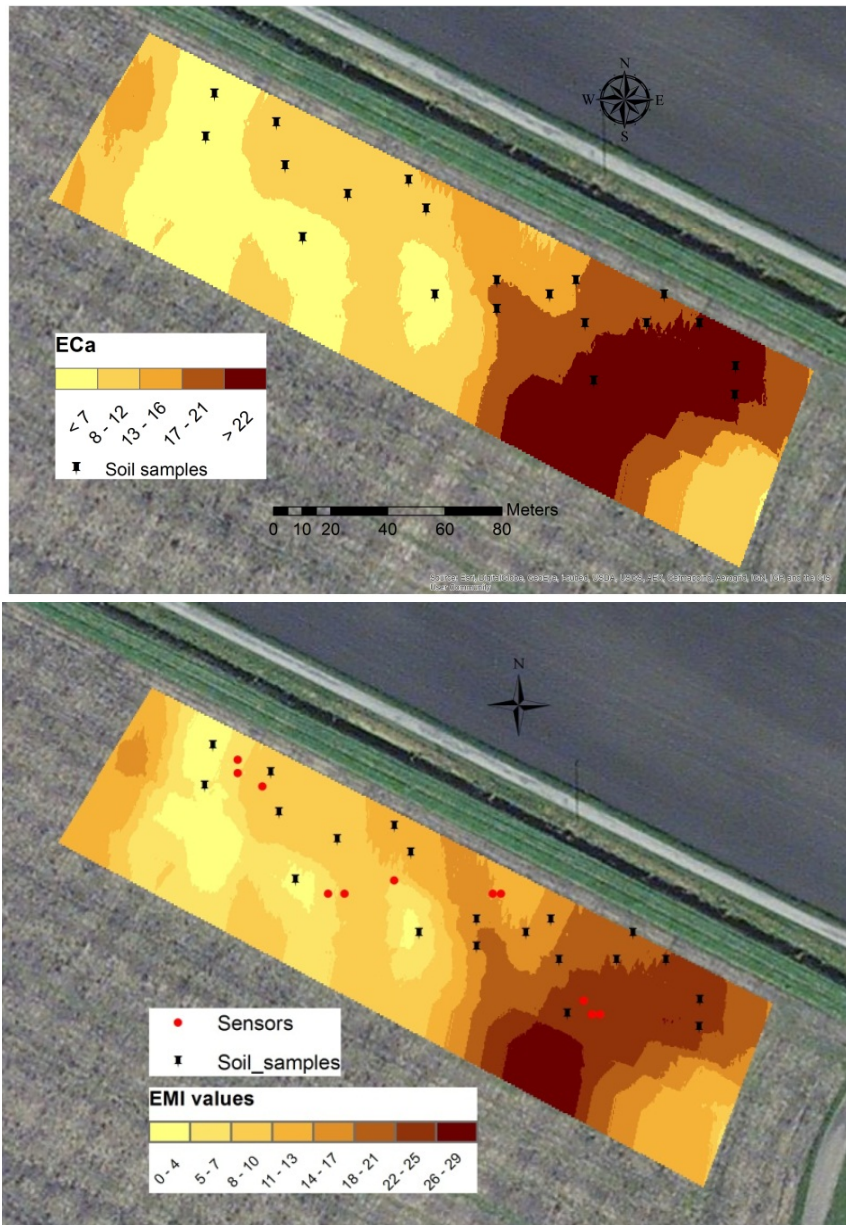
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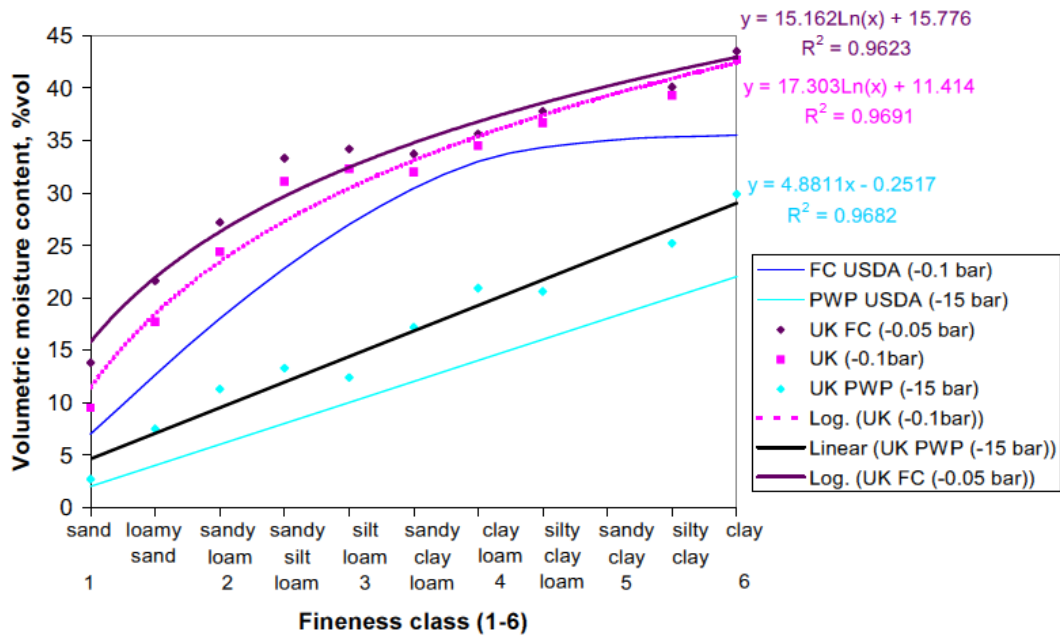
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604 **Figure 1** Spatial variation measured at the lettuce field site (Cambridge, 2012) using EMI
605 technology. The location of soil sampling points are highlighted.



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



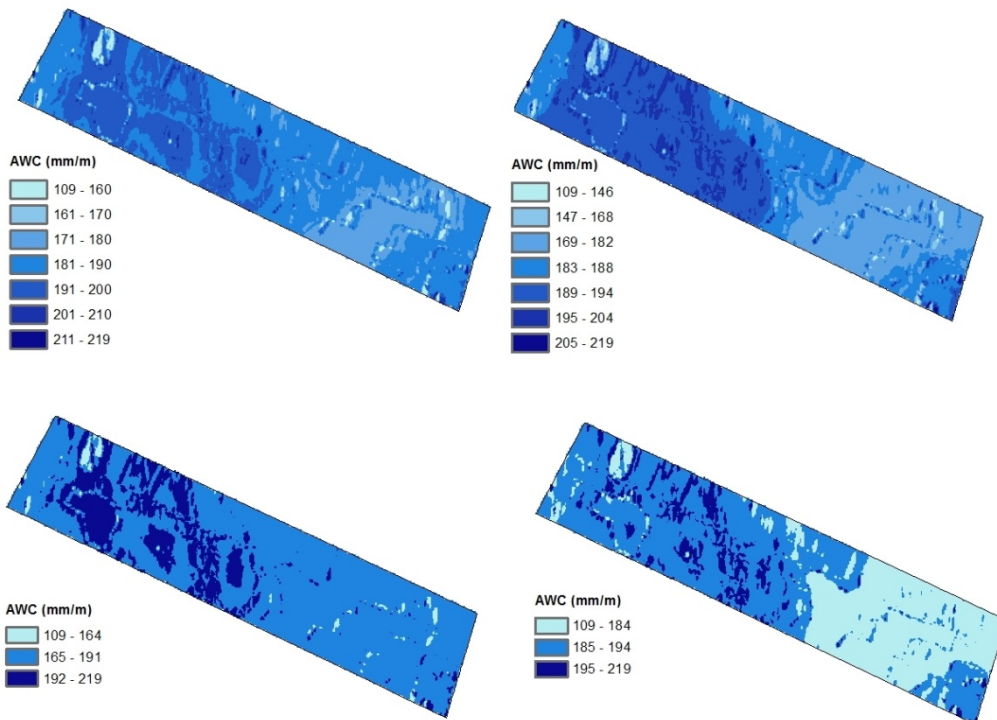
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613 **Figure 3** Maps showing spatial variation in AWC generated from the EMI data, classified
 614 into 7 and 3 classes using equal interval (a) and Jenks natural break (b) methods.

(a) Equal interval method

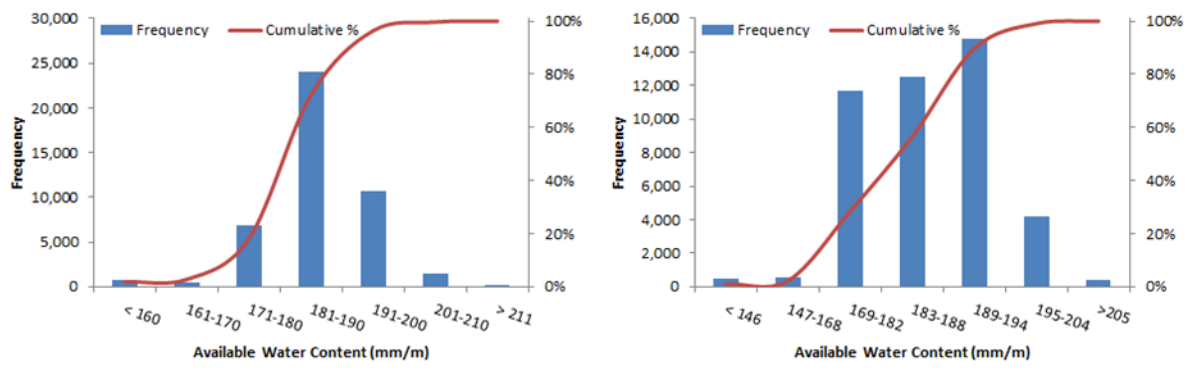
(b) Jenks natural break method



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

(c) Equal interval method

(d) Jenks natural break method



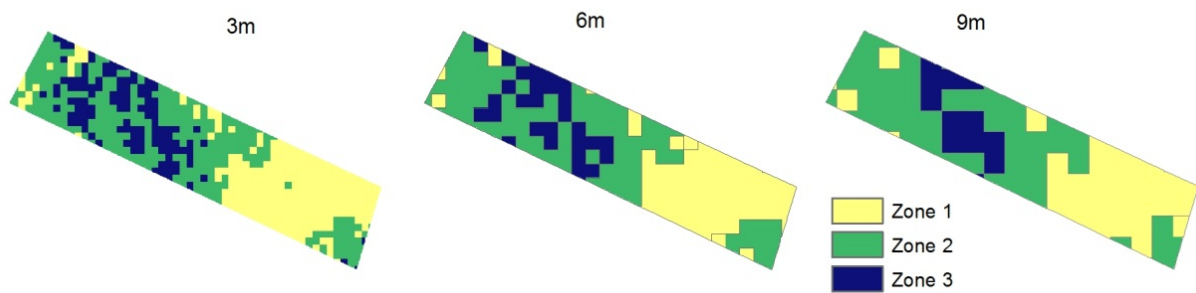
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620 **Figure 5** Irrigation management zones (IMZ) clustered at 3 m², 6 m² and 9m².

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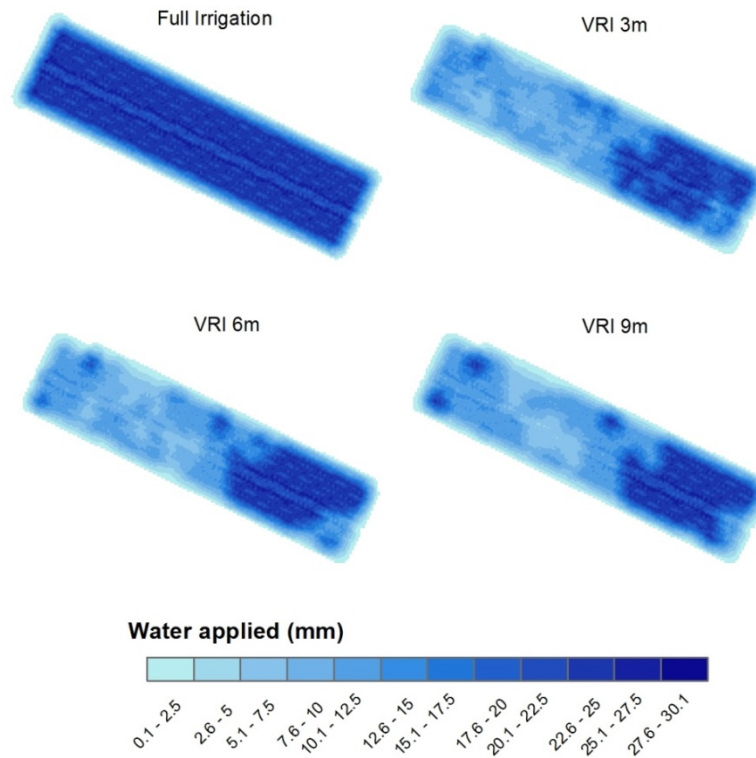
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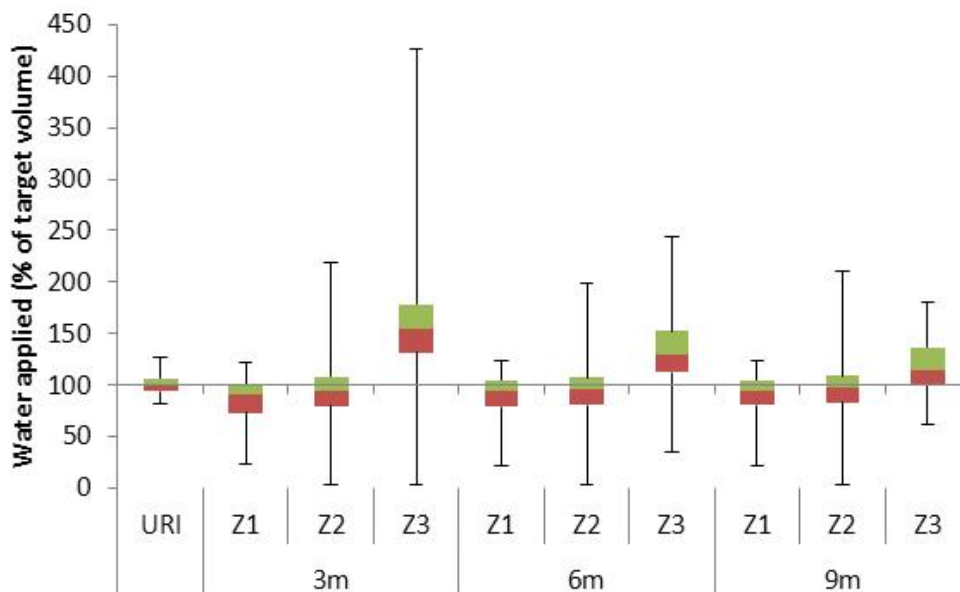
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626 **Figure 6** Spatial distribution of water applied at full uniform irrigation and VRI at 3m², 6m²
 627 and 9m² clustering resolution.



628
 629 **Figure 7** Simulated depths of water applied (mm) in each irrigation management zone under
 630 uniform (URI) and variable rate irrigation (VRI), with the zones defined at 3m, 6m and 9m
 631 scales. Depths are expressed as % of the target application in that zone (100%, 50% and 25%
 632 for Z1, Z2 and Z3, respectively). Boxes represent the median, upper and lower quartile depths
 633 while error bars show the minimum and maximum range.



634