https://doi: 10.17221/116/2017-HORTSCI

Assessing the financial and environmental impacts of precision irrigation in a humid climate

Daniel El Chami[1], Jerry W. Knox[2], André Daccache[3], Edward Keith Weatherhead[2]*

[1]Timac Agro Italia, Ripalta Arpina, Italy
[2]Cranfield Water Science Institute, Cranfield University, Bedfordshire, UK
[3]Department of Biological and Agricultural Engineering, University of California, California, USA

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

Citation: El Chami D., Knox J.W., Daccache A., Wearherhead E.K. (2019): Assessing the financial and environmental impacts of precision irrigation in a humid climate. Hort. Sci. (Prague), 46: 43–52.

Abstract: Precision agriculture is increasingly used where in-field spatial variability exists; however, the benefits of its use in humid climates are less apparent. This paper reports on a cost-benefit assessment of precision irrigation with variable rate technique (VRI) versus conventional irrigation, both compared to rainfed production, using a travelling hose-reel irrigator fitted with a boom on onions in eastern England. Selected environmental outcomes including water savings and CO_2e emissions are evaluated. The modelled precision irrigation system, which responds to soil variability, generates better environmental outcomes than the conventional system in terms of water savings and reduced CO_2e emissions (22.6% and 23.0% lower, respectively). There is also an increase in the 'added value' of the irrigation water used (£3.02/m^3 versus £2.36/m^3). Although precision irrigation leads to significant financial benefits from water and energy savings, these alone do not justify the additional equipment investment costs. However, any changes in yield or quality benefits, equipment costs or greater soil variability than on this site would make investment in precision irrigation more viable.

Keywords: variable rate irrigation; spatial soil variability; environmental impact; cost-benefit analysis

The potential benefits of managing crops using variable rate irrigation (VRI) techniques include financial and environmental benefits obtained as result of higher water use efficiency, energy savings and increased marketable yield and/or crop quality (Hoffman, Martin 1993; Bongiovannim, Lowenberg-Deboer 2004; Ghinassi 2010; McClymont et al. 2012). Nevertheless, the rate of adoption of these technologies has been slower than predicted (McBratney et al. 2005; Hedley et al. 2014). One constraint is the limited number of economic and environmental assessments (Robertson et al. 2007; Smith et al. 2010; Evans, King 2012; Evans et al. 2013). While available literature indicates that other precision technologies can contribute in many ways to long-term environmental and economic sustainability of many agricultural practices e.g. seeding, weeding, pest control (Bongiovanni, Lowenberg-Deboer 2004; Pedersen et al. 2006); published research on the economic benefits of precision irrigation is relatively limited, and what is available shows conflicting results. This is at least partly due to the diversity of factors affecting the systems, many of which have been discussed in previous studies (Almas et al. 2003; Evans, King 2012; Evans et al. 2013), such as in-field and soil variability and the optimal irrigation management zones (IMZ) size, agroclimate,

Supported by the UK Department for Environment, Food and Rural Affairs (Defra) for funding this research through the HortLINK programme (HL0196).

https://doi: 10.17221/116/2017-HORTSCI

crop value, economies of scale and the useful lifespan of the equipment.

In England the value of irrigated production represents around 20% of the total crop output (EA 2007), which amounted in 2014 at 19.3 billion pounds (Defra 2015). The dominant irrigation systems are hose-reel irrigators fitted with either rain-guns or booms (Weatherhead 2007), used on 93% of irrigated agricultural land (Defra 2011). However, water resources are increasingly scarce, with many catchments over-abstracted, and the government is keen to reduce water use, including funding research into precision irrigation.

Nevertheless, only a few studies have assessed the viability of VRI in humid climates such as in northern Europe. Hedley et al. (2009, 2011) modelled the water saving benefits of switching to VRI on linear move sprinkler and centre-pivot systems in three different case studies in New Zealand under different cropping patterns. Despite the high water savings of between 19% and 26%, the authors did not estimate the economic benefits and financial viability of adopting VRI. Similarly, Daccache et al. (2015) examined the technical, agronomic and engineering challenges of applying PI to potato production in the UK, but did not examine the financial aspects.

The objective of this paper was to address this gap in understanding regarding the economics and environmental benefits of precision irrigation with VRI using a travelling hose-reel irrigator fitted with a boom in a humid climate. The research involved the integration of modelling techniques, an approach previously used in the literature to deal with variable application technology in precision agriculture (Hedley et al. 2011; Turker et al. 2011; Ahmad et al. 2012). We established the costs and benefits of conventional and precision irrigation applied to onions (*Allium cepa*) in Eastern England, compared to rainfed production, taking into account agroclimate and soil variability. Selected financial and environmental indicators on the life cycle of the investment were determined, following the framework suggested by El Chami et al (2015) and El Chami and Daccache (2015). Finally, a sensitivity analysis was undertaken to assess the effects of variation in selected production factors.

MATERIAL AND METHODS

The experimental field modelled was previously used as a case study by Pérez-Ortolá et al. (2015) with a total area of 33.9 ha and located in Norfolk (latitude 52.61°N; long 0.56°E; 75 m a.s.l.). Laboratory analysis of 15 soil samples randomly selected from the experimental field showed a free-draining sandy loam Breckland soil (Table 1), slightly alkaline (pH 8.5), with a water content around 10% (Cranfield University 2013). The field was cultivated with spring-sown onion sets (cv. 'Arthur') on

Table 1. Soil analysis results of 15 samples from the experimental field

Sample No.	Sand content (%)	Silt content (%)	Clay content (%)	pH	$CaCO_3$ eq (g/kg)	Organic matter(%)	Field water content (%)	Bulk density (g/cm^3)
1	73.5	16.7	9.8	8.7	66.3	2.5	10.6	1.3
2	70.9	17.6	11.6	8.4	63.6	2.6	11.3	1.3
3	67.0	21.2	11.8	8.6	75.9	2.6	9.9	1.1
4	68.7	18.7	12.6	8.3	74.2	2.6	9.2	1.3
5	68.7	20.0	11.2	8.6	59.7	2.6	9.1	1.0
6	63.0	24.2	12.8	8.5	91.4	2.4	9.7	1.2
7	66.4	21.4	12.2	8.6	157.2	2.7	9.7	1.2
8	68.7	20.0	11.4	8.3	84.8	2.8	12.8	1.0
9	61.1	26.2	12.7	8.7	90.4	2.6	9.8	1.2
10	63.8	24.1	12.1	8.6	88.5	2.6	9.1	1.2
11	67.7	20.0	12.3	8.5	227.5	2.9	10.7	1.3
12	66.2	20.9	12.9	8.5	194.6	2.8	10.5	1.3
13	63.6	22.7	13.7	8.5	76.8	2.7	10.8	1.2
14	66.3	21.7	12.0	8.3	116.3	2.4	9.4	1.2
15	70.0	18.5	11.6	8.5	136.3	2.4	9.2	1.1

https://doi: 10.17221/116/2017-HORTSCI

beds of 1.8 m in width, with each bed holding four rows of onions. The bulbs are drilled in mid-March and harvested at the end of September. Irrigation water was pumped from boreholes on the farm, subject to an abstraction license as required by the Environment Agency (EA), which regulates water resources in England and Wales and sets abstraction charges (EA 2013). Irrigation is applied using a travelling hose-reel irrigator feeding a 64 m wide boom irrigating a 72 m wide strip, with 22 sprinklers (including 2 end impact sprinklers) distributing water at low pressure in fine drops directly above the crop. This type of hose-reel system is simple and easy to operate; they have low labour requirements, are built from long lasting components and require relatively low maintenance.

The field presents relatively low soil heterogeneity; for this study we divided the field into three irrigation management zones (IMZs) based on the results of soil electro-magnetic (EMI) scanning: IMZ 1, a sandy soil, represents 70% of the field area, while IMZ 2, a sandy loam, and IMZ 3, a loamy sand, each represents 15% of the field area, respectively. The boom system modelled was adapted for VRI using individual remotely controlled solenoid valves on each sprinkler, a technology that previously described in the literature both for centre-pivot and linear move systems (Chávez et al. 2010a, b). Each sprinkler was programmed to turn on/off, or pulse as required depending on the spatial variation in irrigation water requirements. The use of pulsed sprinklers allows the irrigation rate to be varied across the boom, in contrast to the simpler approach of varying only the pull-in speed, which only allows variation along the direction of travel.

Irrigation water requirement (IWR) and attainable yield. The daily weather data series used in this modelling were from Brooms Barn experimental station over the 20 years period 1992 to 2011. These data included daily rainfall, reference evapotranspiration (ET_0) and maximum and minimum temperature. The FAO crop model AquaCrop (Doorenbos, Kassam 1979; Steduto et al. 2009) was used to calculate the irrigation water requirements and attainable yield of onions, as a function of water consumption, for the historical weather data and three soil types. AquaCrop has been previously calibrated and validated for onion crops in the UK by Pérez-Ortolá et al. (2015). They advised an irrigation schedule that raises the soil to field capacity whenever the soil moisture deficit reaches 50% of the readily available water (RAW) before the "bulbing" period and 60% after "bulbing".

Financial investment appraisal. A financial investment appraisal (FIA), using discounted cash flow analysis, was carried out to study the different costs and benefits under conventional irrigation (CI) and precision irrigation (PI), compared to rainfed production, and the profits of each investment from the point of view of a private individual or organisation. The production costs outside irrigation are almost identical for rainfed, CI and PI irrigated onion production, and hence are not included in this paper. Irrigation costs include the initial capital costs, the variable costs of applying the irrigation, the annual charges for water abstraction. These costs all vary with the irrigation water requirements and the type of application system (Morris et al. 2017), as well as location. The capital cost of the irrigation systems and precision technology was calculated here based on market figures for similar equipment from a major local equipment supplier (updated for 2014 prices), Briggs Irrigation UK. To obtain an annualised cost, the capital cost was discounted over its assumed useful life (n = 10 years) at a real interest rate of 6%. The additional capital costs for using precision technology relate to the initial mapping of soil properties (using an EMI scanner in this case), the control systems for the sprinklers and the additional soil moisture probes. The number of probes required in turn relates to the heterogeneity of the soil in the field. The fixed costs also include insurance and maintenance, estimated at 1% per annum each. Variable costs related to applying the water e.g. labour costs, tractor usage and the diesel consumption for pumping and for tractor usage, were calculated by updating figures from an economic study in the region by Ahodo (2012).

The annual water abstraction charges (AC) in England in 2013/14 were the sum of the standard charge (calculated under a two-part tariff) plus an environmental compensation charge (added by the regulator for the recovery of compensation costs associated with the revocation or variation of abstraction licences which are causing environmental damage). Under the two-part tariff, half the standard charge is based on the authorised max. annual quantity specified in the license (V_M), modelled here as the water requirement in a dry year under each system. The other half is based on the volume actually abstracted (V_A). The compensation

https://doi: 10.17221/116/2017-HORTSCI

charge is based on the maximum licensed quantity. Unit rates for groundwater abstraction in the Anglian Region in 2013/14 were applied; these range between £0.001/m^3 and £0.154/m^3 depending on the proportion "lost" (i.e. not returned to a water source), the season of abstraction (summer, winter, all year), and whether the flow is supported (e.g. by pumping or reservoir releases), unsupported or tidal (EA 2013). For this site, the abstraction is classified as high loss, unsupported summer abstraction resulting in average water charges of £0.083/m^3. Seasonal water storage (e.g. reservoirs) was not required at this site due to the reliable water supply.

An expanding branch of science has estimated the potential costs of climate change expressed as the "Social Cost of Carbon", defined as the damages caused by each additional ton of carbon dioxide (CO_2) released into the atmosphere (Ackerman, Stanton 2010), and accounting for the other greenhouse gases by using the "carbon dioxide equivalents". To include this cost in the variable costs, we converted the volume of diesel used by the pump and tractor into Global Warming Potential (GWP in t CO_2e) (Defra 2013a) and multiplied it by non-tradable prices of carbon (average price over 10 years: £0.06/kg CO_2e) obtained from DECC (2011).

Financial and environmental indicators. The discounted cash flow analysis assessed selected economic indicators useful for stakeholders' decision making: Net Present Value (NPV in £), Internal Rate of Return (IRR in %), Benefit-Cost Ratio (BCR) and Break-Even Point (B-E in ha). Other indicators calculated related to the effect of the greenhouse gases, the Global Warming Potential (GWP in t CO_2e/ha), as well as some water related indicators defined by Hsiao et al. (2007) and Knox et al. (2011): Irrigation Water Requirement (IWR in m^3/ha), Irrigation Use Efficiency (IUE in t/m) and Added Value of Water (AVW in £/m).

Sensitivity analysis. Modelling tools are very useful for decision-making, but they can hide a lot of uncertainty related to the system they represent and associated to the assumptions and methods of analysis. Sensitivity analysis helps determine which parameters are the key drivers of a model's results and highlights the impact that changes in these parameters will have on the output. The focus of the sensitivity analysis here was to determine the influence of changes in the main input parameters on the benefit ratio y (y = Benefits of PI/Benefits of CI). Having identified the most sensitive parameters, we then adopted the traditional method of examining sensitivity based on derivatives of f (.) evaluated at some "baseline" (or central estimate) $x_i = x_0$ which indicates how the benefit ratio (y) will change if the baseline input values are slightly perturbed. This method has the advantage of giving a quantitative value of the change in the ratio (y).

RESULTS

This section describes firstly the calculation of irrigation water requirements and attainable yield under variable rate and uniform rate of irrigation, then the costs and benefits of these practices compared to the rainfed production and finally the selected economic and environmental indicators. We compare both precision and conventional irrigation against the rainfed production because this gives a comparative image of the returns from each irrigation technique.

Irrigation water requirement (IWR) and attainable yield

The irrigation water requirements of onion over the past 20 years (from 1992 to 2011) were modelled ranked and plotted against the rainfed and irrigated yield (Fig. 1). The analysis is presented for three different types of 'weather year', based on those ranked irrigation needs, plus the 'overall mean' values:

– 'Wet years', based on the means of the 25% with lowest irrigation need;

– 'Normal years', defined as the means of the central 50% years ranked on irrigation need;

– 'Dry years', based on the means of the 25% with highest irrigation need;

– 'Overall mean', showing the means calculated across all 50 years.

The modelled irrigation water requirements (IWR) and the rainfed and irrigated yields for both precision and conventional irrigation and for each of these climate years and the 'overall mean' are shown in Table 2 for each IMZ.

To estimate the actual water applied under conventional irrigation we assumed the modelled requirements for the sandy loam soil, representing the "driest" part of the field (i.e. with the highest IWR) would be applied to the whole field. In contrast, for precision irrigation we assumed the modelled requirement was

https://doi: 10.17221/116/2017-HORTSCI

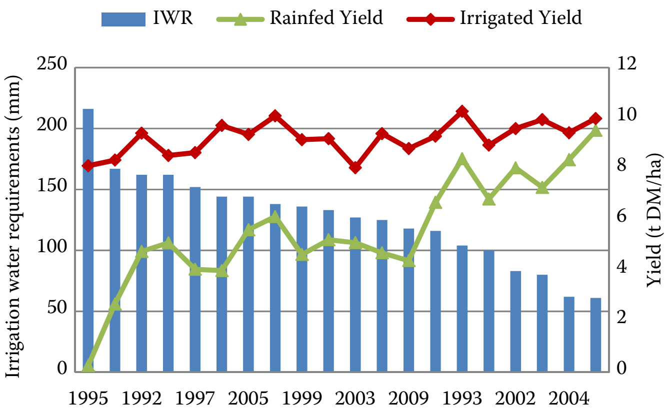

Fig. 1. Modelled irrigation water requirements (IWR), rainfed yield and irrigated yield for 1992 to 2011, ranked by IWR

Table 2. Modelled irrigation water requirement (IWR) and yields for different weather years and soils

	IWR (m^3/ha)	Yield (t/ha)	
		rainfed	irrigated
Conventional Irrigation			
Total field			
Wet years	1,114	62	74
Dry years	2,456	24	67
Normal years	1,814	42	73
Overall mean	1,800	43	72
Standard deviation	548	15.5	3.0
Precision irrigation			
IMZ 1 (sandy soil)			
Wet years	772	62	74
Dry years	1,718	26	66
Normal years	1,285	42	72
Overall mean	1,265	43	71
Standard deviation	386.7	14.6	3.2
IMZ 2 (sandy loam)			
Wet years	1,114	69	77
Dry years	2,456	28	71
Normal years	1,814	49	75
Overall mean	1,800	49	75
Standard deviation	548.0	16.5	2.5
IMZ 3 (loamy sand)			
Wet years	956	58	75
Dry years	2,142	12	69
Normal years	1,621	37	73
verall mean	1,585	36	73
Standard deviation	485.4	19.0	2.7
Total field			
Wet years	851	62	74
Dry years	1,892	24	67
Normal years	1,415	42	73
Overall mean	1,393	43	72
Standard deviation	425.5	15.5	3.0

applied to each IMZ; the average water need is then the sum of the water need per IMZ multiplied by the proportion of the area that IMZ represents. Only net volumes were considered; losses were assumed to be similar under each system.

The modelled yield of the rainfed crop is lowest for the years with highest irrigation need, and hence highest water stress, as expected. The small fluctuations seen in the irrigated yield partly reflect temperature variations rather than changes in water stress. The irrigated yield was therefore assumed here to be the same under both conventional and precision irrigation for the economic analysis; any additional yield and/or improved crop quality from PI would be an additional benefit.

Financial investment appraisal

The capital cost of the basic hose-reel irrigation system for conventional irrigation was calculated at £286/ha when expressed as an annual charge. The sensing technology, control and EMI scanning costs add a further £101/ha and £199/ha per annum for CI and PI, respectively.

The overall mean annual abstraction charges amounted for £149/ha and £114/ha for CI and PI respectively, with an inter-annual variation depending on the weather year (Fig. 2). The variable costs of the irrigation system (pumping, labour and tractor use) were £167/ha and £153/ha respectively, and the estimated social cost of carbon were £16/ha and £13/ha respectively. These figures varied according to the weather year. The variations in the abstraction, application and SCC costs reflect both the higher water usage in drier years for both systems and the smaller quantity of water needed for the precision irrigation system.

https://doi: 10.17221/116/2017-HORTSCI

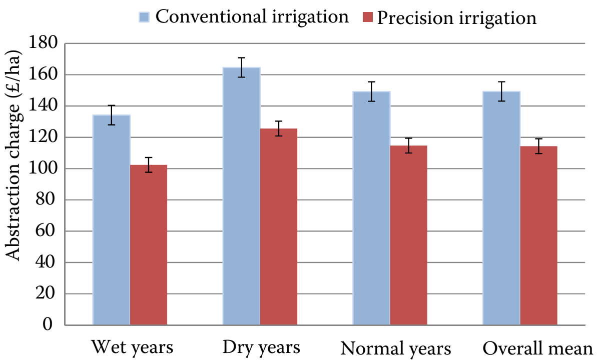

Fig. 2. Annual water abstraction charges for conventional irrigation and precision irrigation in different weather years

Thus, the overall mean total costs were £720/ha and £766/ha for CI and PI, respectively. Hence, despite savings in water and energy, the modelled precision irrigation system was more expensive overall. The results also show that capital costs dominate in both systems, in all types of weather year.

The marketable yield was estimated by dividing the dry matter yields (DM) generated by the model by 13%, based on laboratory analysis of onions from the experimental field (Pérez-Ortolá et al. 2015). For irrigated onions, the marketable yield was multiplied by the onion price considered at £170/t, which is the average historical market price in the UK between 2003 and 2012 at the farm gate (Defra 2013b). We reduced the price for the rainfed crops to allow for the lower quality, by 24% in a dry year, 17% in an average year and 10% in a wet year, based on previous research by Morris et al. (1997). We also deducted the additional costs for harvest, curing and storage of the additional yield, estimated at £40/t (*pers. comm.*). Finally, the costs and benefits of conventional and precision irrigation are compared, and the net profits were estimated (Table 3). Results show that the net profits from precision irrigation are still below those from conventional irrigation by about 0.7% overall.

Table 3. Financial investment appraisal under conventional and precision irrigation

	Wet years	Dry years	Normal years	Overall mean
Conventional irrigation (CI)				
Additional marketable product (t/ha)	12.3	43.2	30.1	28.9
Price (£/t)	170	170	170	170
Quality benefits on rainfed (%)	10	23	17	17
Total Benefits (£/ha)	3,144	8,296	6,353	6,160
Abstraction charges (£/ha)	132	162	148	148
Irrigation costs (£/ha)	422	547	485	485
Extra-costs of irrigation (£/ha)	491	759	1,205	1,157
Sensing technology (£/ha)	112	112	112	112
Social costs (£/ha)	10	23	17	16
Total costs (£/ha)	1,167	1,603	1,967	1,918
Profits from CI (£/ha)	1,977	2,575	4,383	4,242
Precision irrigation (PI)				
Additional marketable product (t/ha)	12.3	43.2	30.1	28.9
Price (£/t)	170	170	170	170
Quality benefits on rainfed (%)	10	23	17	17
Total benefits (£/ha)	3,144	8,296	6,353	6,160
Abstraction charges (£/ha)	102	125	114	114
Irrigation costs (£/ha)	400	488	445	445
Sensing technology (£/ha)	221	221	221	221
Extra-costs of irrigation (£/ha)	4 91	1,728	1,157	1,205
Social costs (£/ha)	8	17	13	13
Total costs (£/ha)	1,221	2,578	1,293	1,949
Profits from PI (£/ha)	1,924	5,717	5,060	4,211
Benefit ratio (£/ha)	0.97	0.22	1.15	0.99

Financial and environmental benefits

The resulting financial and environmental indicators are shown in Table 4. Even though the financial indicators show a slight advantage for conventional irrigation over precision irrigation, the environmental indicators show clearly the positive externalities generated using precision irrigation, reflecting the reduced water usage (22.6% lower in PI) and consequently the higher Irrigation Use Efficiency (IUE). The added value of the water applied (AVW) increases from £2.4/m to £3.0/m, while the global warming potential in terms of CO_2e emissions is 23.0% lower for PI.

Sensitivity Analysis

The parameters that have a high impact on the benefit ratio *y* (*Benefits PI/Benefits CI*) are yield difference (*Yield under PI/Yield under CI*) and difference in irrigation water requirements (*IWR under PI – IWR under CI*). A 1% increase in yield under precision irri-

https://doi: 10.17221/116/2017-HORTSCI

Table 4. Selected 'overall mean' performance indicators for conventional irrigation and precision irrigation

Indicators	Conventional	Precision
Net present value (NPV) (£/ha)	42,108	42,200
Internal rate of return (IRR) (%)	262	240
Benefit-cost ratio (BCR)	14	14.4
Break-even point (B-E) (ha)	16.1	17.9
Irrigation water requirement (IWR) (m^3/ha)	1,800	1,393
Irrigation use efficiency (IUE) (t/m^3)	0.041	0.053
Added-value of water (AVW) (£/m^3)	2.36	3.02
Global warming potential (GWP) (t CO_2e/ha)	0.28	0.2

Table 5. Sensitivity analysis of the benefit ratio (y) to $\Delta Y_{irrigated}$ and ΔIWR

$\Delta Y_{irrigated}$ = $Yield_{irrigated}$ under PI – $Yield_{irrigated}$ under CI						
– 20%	**– 10%**	**– 1%**	$\Delta Y_{irrigated}$	**+ 1%**	**+ 10%**	**+ 20%**
– 58.3%	– 29.5%	– 3.6%	**– 0.7%**	+ 2.2%	+ 28.0%	+ 56.8%
ΔIWR = IWR under PI – IWR under CI						
– 50%	**– 25%**	**– 10%**	ΔIWR	**+ 10%**	**+ 25%**	**+ 50%**
+ 0.6%	– 0.1%	– 0.5%	**– 0.7%**	– 1.0%	– 1.4%	– 2.1%

bold values – central values; IWR – irrigation water requirement; CI – conventional irrigation; PI – precision irrigation

gation compared to conventional irrigation increases the benefit ratio by 2.9%, while a 25% reduction in water use has only minor impact (Table 5). The final sensitivity analysis was to test how the benefit ratio (y) responds to the change in soil variability (Table 6), so ten different scenarios (Case) with different variability rates where hypothesised. Much of the literature reviewed suggested a correlation between viability of PI and soil variability (Marek et al. 2001; Almas et al. 2003). The model was run with different soil combinations and benefits were calculated. Even though the ratio of change is not very large, the analyses confirm that the benefits are positively related to the degree of soil variability.

Table 6. Sensitivity analysis of the benefit ratio (y) to soil variability

Case	Soil variability	(%)
1	IMZ 1: 70%, IMZ 2: 15%, IMZ 3: 15%	–1.09
2	IMZ 1: 15%, IMZ 2: 70%, IMZ 3: 15%	–2.07
3	IMZ 1: 15%, IMZ 2: 15%, IMZ 3: 70%	–1.36
4	IMZ 1: 33.3%, IMZ 2: 33.3%, IMZ 3: 33.3%	–1.49
5	IMZ 1: 100%, IMZ 2: 0%, IMZ 3: 0%	–0.74
6	IMZ 1: 0%, IMZ 2: 100%, IMZ 3: 0%	–2.64
7	IMZ 1: 0%, IMZ 2: 0%, IMZ 3: 100%	–1.27
8	IMZ 1: 50%, IMZ 2: 25%, IMZ 3: 25%	–1.32
9	IMZ 1: 25%, IMZ 2: 50%, IMZ 3: 25%	–1.74
10	IMZ 1: 25%, IMZ 2: 25%, IMZ 3: 50%	–1.43

IMZ – irrigation management zones

DISCUSSION

Fitting precision irrigation technology to mobile irrigation systems such as hose-reels raises several issues. In the UK, a typical crop rotation would include both irrigated and non-irrigated crops (e.g. wheat). There are thus benefits from the hose-reel's mobility compared to fixed pivot systems in that the equipment can follow the irrigated crops around the farm, avoiding the rotational impacts on financial viability noted by King et al. (2006). However, it does complicate the control system required, as the boom must be aware of its position relative to the IMZs. It is also necessary to undertake the soil mapping for each field in the rotation. A fairly simple form of PI was modelled here, which responds only to soil type. A more complex system relating to real-time soil moisture or crop stress measurements would require more complex sensors and controls.

In this study, both forms of irrigation were shown to be considerably more beneficial financially than

https://doi: 10.17221/116/2017-HORTSCI

rainfed production of onions. The appraisal (Table 3) showed that the financial benefits for conventional irrigation are still slightly higher overall than for precision irrigation, particularly in the wetter years when water use is lowest. This supports the common-sense observation that investments in PI are more justified in drier regions and for crops where water use is highest.

The financial and environmental advantages of adopting precision irrigation rather than conventional irrigation considered here are in terms of water savings and reducing CO_2e emissions. Both are around 20% lower for PI compared to CI. These results are in general accordance with Evans and King (2012) who reported water savings of 0% to 26% from different case studies across the USA, and Al-Kufaishi et al. (2006) who showed under similar climate conditions, precision agriculture is the best option for water conservation in a sugar-beet field in Germany.

In this study the attainable yield was deliberately assumed to be the same under both CI and PI. In contrast, Lu et al. (2005) showed in South Carolina (USA) under PI that corn yield could increase by between 1.7% and 2.2% depending on the irrigation scheduling, compared to CI; and Simmonds et al. (2013) estimated a 7.1% to 14.5% increase in yield in rice systems under precision management in California (USA). A similar increase would make PI in this case study financially viable, as shown by the sensitivity analysis in Table 5. This could be further enhanced by crop quality and consistency benefits due to the reductions in water stress (from both under-watering and over-watering) in the different IMZs, and resultant increases in crop price, storability and saleability.

Similarly, the water has been costed here in terms only of abstraction charges and application costs. Under water scarcity constraints, which are becoming increasingly common in the UK, the opportunity cost of water can be very much higher. Many irrigators are now constructing farm reservoirs for water shortage; Morris et al. (2014) calculated this adds around £0.18/m^3 to the cost, which would make the water savings much more valuable. Furthermore, the value of water saved for use on competing crops, such as potatoes, can be as high as £1.50/m^3 (Morris et al. 2014). Hence the benefits in water scarce catchments and on farms with limited access to water resource are significantly higher, albeit very farm specific and difficult to evaluate precisely.

We have made no allowance for climate change in the IWR modelling. Previous studies (Daccache et al. 2012) have suggested both higher IWR and larger areas of high value crops will need irrigating in the UK in future, which would also further increase water scarcity, and hence raise the benefits of PI. More experimental research is required to collect and evaluate data on yield and quality benefits, and more farm modelling is required to evaluate site specific benefits.

This analysis has a few inherent limitations. First of all, the AquaCrop model does not consider yield reduction due to water stress from over-irrigation, as might occur in some parts of a conventionally irrigated field; however, these would be minimal in the well-drained soil assumed. We have not considered any additional management costs for precision irrigation; these should be fairly minor for this system that responds only to the pre-mapped IMZs, whereas more interactive precision systems, e.g. responding to on-going crop development, would have significant additional management costs. The division into three IMZs was also arbitrary, and the number and limits of each zone could perhaps be optimised. Selecting the market value for the onions is problematic. It was taken here as the average price between 2003 and 2012, at £170/t. In that time, it has oscillated from £86/t in 2005 to £300/t in 2010 and back to £161/t in 2012. A more fundamental limitation, which also applies to all the previous modelling studies, is that the conditions and the irrigation within each IMZ have been assumed to be uniform. In practice, there will still be non-uniformity in the field, as it is impossible to apply the exact volume of water and uniformly within each IMZ boundary. Together, these limitations may reduce the advantages of precision irrigation, though it is very difficult to estimate by how much.

CONCLUSIONS

This study integrated modelling tools to simulate the benefits of precision irrigation (PI) and conventional irrigation (CI), compared to rainfed production, for an onion crop grown in a typical humid climate (East of England, UK) using a hose-reel fitted with a boom system. Aquacrop was used to simulate IWRs and corresponding yields for three different soil types (Sandy, Sandy Loam and Loamy Sand). We considered three IMZ in-field (not optimised) and weighted the IWRs and yields with the corresponding percentage areas. The modelling indicated significant water savings and energy saving

https://doi: 10.17221/116/2017-HORTSCI

benefits from precision irrigation. These alone do not cover the additional operating costs. However, crop yield or quality benefits, higher water savings and/or greater soil variability would make investment in precision irrigation more viable. Optimisation of the precision irrigation system management could also give significant improvements. Given the promising environmental benefits in terms of water saving and CO_2 emission reduction, more studies are recommended to inform farmers, who are the potential users of this technology in the future, and policy makers, who are obliged under the EU Water Framework Directive (EU-WFD) to implement measures to reduce water use. This study can provide a useful framework for future evaluations.

Acknowledgment

Industry support for market prices of equipment (Briggs Irrigation UK) is gratefully acknowledged.

References

Ackerman F., Stanton E.A. (2010): The social cost of carbon. Real-World Economics Review, 53: 129–143.

Ahmad S., Ahmad A., Tojo Soler C.M., Ali H., Zia-Ul-Haq M., Anothai J., Hussain A., Hoogenboom G., Hasanuzzaman M. (2012): Application of the CSM-CERES-Rice model for evaluation of plant density and nitrogen management of fine transplanted rice for an irrigated semiarid environment. Precisison Agriculture, 13: 200–218. doi: 10.1007/s11119-011-9238-1

Ahodo K. (2012): Economics of Potato irrigation in the UK. [MSc Thesis.], School of Applied Sciences, Cranfield University.

Al-Kufaishi S.A., Blackmore B.S., Sourel H. (2006): The feasibility of using variable rate water application under a central pivot irrigation system. Irrigation and Drainage Systems, 20: 317–327. doi: 10.1007/s10795-006-9010-2

Almas L.K., Amosson S.H., Marek T., Arden Colette W. (2003): Economic feasibility of precision irrigation in the Northern Texas High Plains. In: The Southern Agricultural Economics Association Annual Meeting.

Bongiovanni R., Lowenberg-Deboer J. (2004): Precision agriculture and sustainability. Precision Agriculture, 5: 359–387. doi: 10.1023/B:PRAG.0000040806.39604.aa

Chávez J.L., Pierce F.J., Elliott T.V., Evans R.G. (2010a): A remote irrigation monitoring and control system for continuous move systems. Part A: description and development. Precision Agriculture, 11: 1–10. doi: 10.1007/s11119-009-9109-1

Chávez J.L., Pierce F.J., Elliott T.V., Evans R.G., Kim Y., Iversen W.M. (2010b): A remote irrigation monitoring and control system (RIMCS) for continuous move systems. Part B: field testing and results. Precision Agriculture., 11: 11–26.

Cranfield University (2013): The Soils Guide. Available at www.landis.org.uk. Cranfield University, UK. (accessed Oct 21, 2013)

Daccache A., Keay C., Jones R.J.A., Weatherhead E.K., Stalham M.A., Knox J.W. (2012): Climate change and land suitability for potato production in England and Wales: impacts and adaptation. Journal of Agriculture Science, 150: 161–177. doi: 10.1017/S0021859611000839

Daccache A., Knox J.W., Weatherhead E.K., Daneshkhah A., Hess T.M. (2015): Implementing precision irrigation in a humid climate – Recent experiences and on-going challenges. Agricultural Water Management, 147: 135–143. doi:10.1016/j.agwat.2014.05.018

DECC (2011): A brief guide to the carbon valuation methodology for UK policy appraisal. Department of Energy & Climate Change (DECC). Available at www.gov.uk

Defra (2011): Water usage in agriculture and horticulture – Results from the Farm Business Survey 2009/10 and the Irrigation Survey 2010. Department for Environment, Food & Rural Affairs (Defra). Available at www.gov.uk

Defra (2013a): Government conversion factors for company reporting. Greenhouse Gas Conversion Factor Repository. Department for Environment, Food & Rural Affairs (Defra). Available at http://www.ukconversionfactorscarbonsmart.co.uk/

Defra (2013b): Basic Horticultural Statistics 2013. Department for Environment, Food & Rural Affairs (Defra), UK. Available at www.gov.uk

Defra (2015): Agriculture in the United Kingdom 2014. Department for Environment, Food & Rural Affairs (Defra), UK. Available at www.gov.uk

Doorenbos J., Kassam A.H. (1979): Yield response to water. Irrigation and Drainage Paper No. 33. Food and Agriculture Organization of the United Nations (FAO).

EA (2007): A fair share of water for agriculture – A strategy for irrigation in Eastern England. Environment Agency, Bristol, UK.

EA (2013): Abstraction Charges Scheme 2013/14. Environment Agency, Bristol, UK.

El Chami D., Daccache A. (2015): Assessing sustainability of winter wheat production under climate change scenarios in a humid climate – An integrated modelling framework. Agricultural Systems, 140: 19–25. doi: 10.1016/j.agsy.2015.08.008

El Chami D., Knox J.W., Daccache A., Weatherhead E.K. (2015). The economics of irrigating wheat in a humid climate – A study in the East of England. Agricultural Systems, 133: 97–108. doi: 10.1016/j.agsy.2014.11.001

https://doi: 10.17221/116/2017-HORTSCI

Evans R.G., King B.A. (2012): Site-specific sprinkler irrigation in a water-limited future. Transaction of the ASABE, 55: 493–504. doi:10.13031/2013.35829

Evans R.G., LaRue J., Stone K.C., King B.A. (2013): Adoption of site-specific variable rate sprinkler irrigation systems. Irrigation Science, 31: 871–887. doi: 10.1007/s00271-012-0365-x

Ghinassi G. (2010): Advanced technologies applied to hose reel rain-gun machines: New perspectives towards sustainable sprinkler irrigation. In: XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR): 13–17 June, Québec City, Canada.

Hedley C., Bradbury S., Watson E., Dalrymple H., Wright J. (2011): Farm scale trials of variable rate irrigation to assess the benefits of modifying existing sprinkler systems for precision application. International Journal of Agricultural Management, 1: 51–55.

Hedley C.B., Knox J.W., Raine S.R., Smith R. (2014): Water: Advanced irrigation technologies. In: Encyclopedia of Agriculture and Food Systems, 2nd Ed., Elsevier: 378–406.

Hedley C.B., Yule I.J., Tuohy M.P., Vogeler I. (2009): Key performance indicators for simulated variable-rate irrigation of variable soils in humid regions. Transactions of the ASABE, 52: 1575–1584.

Hoffman G.J., Martin D.L. (1993): Engineering systems to enhance irrigation performance. Irrigation Science, 14: 53–63. doi: 10.1007/BF00208398

Hsiao T.C., Steduto P., Fereres E. (2007): A systematic and quantitative approach to improve water use efficiency in agriculture. Irrigation Science, 25: 209–231. doi: 10.1007/s00271-007-0063-2

King B.A., Stark J.C., Wall R.W. (2006): Comparison of site-specific and conventional uniform irrigation management for potatoes. Applied Engineering in Agriculture, 22: 677–688.

Knox J.W., Daccache A., Hess T.M., Else M., Kay M., Burton M., Malano H. (2011): Benchmarking agricultural water use and productivity in key commodity crops. Cranfield University, Cranfield, England.

Lu Y.-C., Sadler E.J., Camp C.R. (2005): Economic feasibility study of variable irrigation of corn production in Southeast Coastal Plain. Journal of Sustainable Agriculture, 26: 69–81. doi: 10.1300/J064v26n03_08

Marek T., Almas L., Cox E., Amosson S. (2001): The feasibility of variable rate irrigation with center pivot systems in the Northern Texas High Plains. 2001 ASAE Annual International Meeting Paper No.01-1117. St. Joseph, MI: American Society for Agricultural Engineers.

McBratney A., Whelan B., Ancev T., Bouma J. (2005): Future directions of precision agriculture. Precision Agriculture, 6: 7–23. doi: 10.1007/s11119-005-0681-8

McClymont L., Goodwin I., Mazza M., Baker N., Lanyon D.M., Zerihun A., Chandra S., Downey M.O. (2012): Effect of site-specific irrigation management on grapevine yield and fruit quality attributes. Irrigation Science, 30: 461–470.

Morris J., Else M.A., El Chami D., Daccache A., Rey D., Knox J.W. (2017): Essential irrigation and the economics of strawberries in a temperate climate. Agricultural Water Management, 194: 90–99. doi: 10.1016/j.agwat.2017.09.004

Morris J., Ahodo K., Weatherhead E.K., Daccache A., Patel A., Knox J.W. (2014): Economics of rainfed and irrigated potato production in a humid environment. In: Bournaris T., Berbel J., Manos B., Viaggi D. (eds): Economics of Water Management in Agriculture. CRC Press: 71–97.

Morris J., Weatherhead E.K., Mills J., Dunderdale J.A.L., Hess T., Gowing D.J.G., Sanders C., Knox J.W. (1997): Spray irrigation cost benefit study. Final Report, Cranfield University, Cranfield, England.

Pedersen S.M., Fountas S., Have H., Blackmore B.S. (2006): Agricultural robots–system analysis and economic feasibility. Precision Agriculture, 7: 295–308. doi: 10.1007/s11119-006-9014-9

Pérez-Ortolá M., Daccache A., Hess T.M., Knox J.W. (2015): Simulating impacts of irrigation heterogeneity on onion (*Allium cepa* L.) yield in a humid climate. Irrigation Science, 33: 1–14. doi: 10.1007/s00271-014-0444-2

Robertson M., Carberry P., Brennan L. (2007): The economic benefits of precision agriculture: Case studies from Australian grain farms. The Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Simmonds M.B., Plant R.E., Peña-Barragán J.M., van Kessel C., Hill J., Linquist B.A. (2013): Underlying causes of yield spatial variability and potential for precision management in rice systems. Precision. Agriculture, 14: 512–540. doi: 10.1007/s11119-013-9313-x

Smith R.J., Baillie J.N., McCarthy A.C., Raine S.R., Baillie C.P. (2010): Review of precision irrigation technologies and their application. A report for National Program for Sustainable Irrigation, National Centre for Engineering in Agriculture. University of Southern Queensland, NCEA Publication 1003017/1.

Steduto P., Hsiao T.C., Raes D., Fereres E. (2009): AquaCrop – The FAO crop model to simulate yield response to water: I. concepts and underlying principles. Agronomy Journal., 101: 426–437. doi: 10.2134/agronj2008.0139s

Turker U., Erdem T., Tagarakis A., Mitev G., Akdemir B., Gemtos T.A. (2011): A feasibility study of variable rate irrigation in black sea area: Water and energy saving from the application. Journal of Information Technology in Agriculture, 1: 1–6.

Weatherhead E.K. (2007): Survey of irrigation of outdoor crops in 2005 – England and Wales. Cranfield University.

Received for publication June 23, 2017
Accepted after corrections May 29, 2018