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Modelling and mapping the economic value of supplemental irrigation in a humid climate

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ABSTRACT

Irrigation is an essential component of crop production to meet retailer demands for premium quality when rainfall is insufficient. Under drought conditions, irrigation can be constrained by water resources availability, with consequent impacts on yield, quality and revenue. Whilst most agriculture in Europe is rainfed, greater dependence on supplemental irrigation could become more important in humid environments due to a changing climate with greater rainfall uncertainty and higher frequency of droughts. By combining industry and farm level economic data, with geospatial information on agricultural land use, agroclimate, soils and irrigation practices within a GIS, this paper estimates the total financial benefit of outdoor irrigated production in England and Wales assuming no constraints in resource availability and optimal irrigation practices. The analysis suggests that the total net benefits of irrigation in a 'design' dry year are around £665 million, with an average irrigation water productivity in excess of £3.3 per m^3 (close to £1.1 per m^3 excluding soft fruit). Map outputs highlight significant regional differences in water productivity reflecting the composition of land use and the importance of crop mix in determining economic value. A sensitivity analysis to changes in agroclimate, market conditions (crop prices) and water supply (costs) illustrates how the benefits might change under contrasting scenario. The study highlights the importance of supplemental irrigation, even in a humid climate, and the risks that future droughts and/or constraints in water resource availability might have on agricultural systems, livelihoods and the rural economy. The implications for water resources and drought management are discussed.

1. Introduction

Water is becoming an increasingly scarce resource, not only in arid and drought-prone areas but also in more humid and temperate regions where traditionally rainfall has been abundant (Santos Pereira et al., 2002; Daccache et al., 2012). A drought is normally defined as a natural hazard caused by a period of abnormally low precipitation. Three main types of droughts can be distinguished: a meteorological drought, an agricultural drought, a hydrological drought. A fourth type, socio-economic drought, can also be defined, dealing with drought in terms of supply and demand, taking into account the impact of water shortages on socio-economic systems (Wilhite and Glantz, 1985). A meteorological drought is characterised by a prolonged period of low rainfall; an agricultural drought occurs when a lack of precipitation results in low soil moisture that affects crop growth and development; and a hydrological droughts typically occurs when precipitation deficits lead to below normal water levels in reservoirs and rivers for an extended period (AMS Council, 2013). Over the last three decades, the incidence of droughts in Europe has increased in both intensity and number, mainly in the Mediterranean region (European Commission, 2007). The risk of drought and water scarcity is expected to increase in future in currently dry regions due to a range of factors including climate change and population growth (IPCC, 2014). The agricultural sector is particularly sensitive to drought and water scarcity because of its dependence on water, along with other weather-related factors (Knox et al., 2010a). Agriculture is the dominant user of freshwater in many countries, accounting for 70% of global water withdrawals (FAO, 2004; Calzadilla et al., 2010). Most irrigation occurs in arid and semi-arid areas where there is insufficient rainfall to support crop growth. In these areas, the inter-annual variability in irrigation application is relatively small as irrigation provides the majority of crop water requirements to sustain crop growth. Whilst such areas have tended to be the focus for most research on irrigation demand assessment, water efficiency and economic valuation (Hillel, 1987; Oweis, 1997; Deng et al., 2006; Prasad et al., 2006),

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supplemental irrigation can also be critical in humid regions where it buffers the effects of rainfall variability so that the adverse effects of low soil moisture content on crop development and particularly quality are reduced (Oweis, 2005).

Given an increasing emphasis on quality assurance, rather than solely yield, supplemental irrigation is essential to ensure the viability and profitability of particular crops in some regions. For example, there has been a marked increase in irrigation of high-value crops such as potatoes and field vegetables in the UK (Morris et al., 2014). However agricultural irrigation is often given the lowest priority for water allocation under drought conditions. This partly reflects a perception that the marginal value of water is relatively low in agriculture compared to its use in other sectors including public water supply, and that there is scope in drought conditions for increasing the 'efficiency in use' of agricultural irrigation. However, in humid regions, the small application depths applied to high-value crops primarily for quality assurance purposes can result in very high financial benefits, and hence the potential economic impacts of any water shortages (abstraction restrictions) can be substantial (Knox et al., 2000).

In order to guarantee public water supply and maintain minimum environmental flows during droughts, the water regulatory agency in England and Wales (Environment Agency, EA) can impose partial or total bans on irrigation abstraction (EA, 2012; Defra, 2014), so water may not be available to farmers when needed (Knox et al., 2010b). This has occurred during recent drought episodes in 1995, 2003, 2006 and 2011–2012 (ADAS, 1999; Marsh, 2004; EA, 2006; EA, 2011a). For instance, formal restrictions were imposed on 600 spray irrigation licences during the 2006 drought, and 300 irrigators were affected by abstraction restrictions in the 2012 drought (EA, 2011b; Vivid Economics, 2013). Hess et al. (2011) estimated that more than half of the total area of irrigated production in England and Wales is currently located in catchments designated as being either 'over-abstracted' and/or 'over-licensed'; these areas are therefore the focus of increasing attention to support more sustainable levels of abstraction through regulatory reform and the revocation of so-called 'time-limited' licences (perpetuity). In order to protect their interests some farmers have formed water abstractor groups (WAGs) to collectively share their risks and knowledge (Leathes et al., 2008), whilst others have taken individual actions including investment in storage reservoirs and precision irrigation.

Drought combined with restrictions on irrigation abstraction can therefore have important agronomic and economic impacts on crop production. Whilst the impacts of drought on the value of output from UK agriculture as a whole have been assessed (e.g. ADAS (1999) for the 1995 drought; and Anglian Water and University of Cambridge (2013) for the 2010–2012 drought), there is much less understanding of the economic impacts of restrictions on supplemental irrigation in field-scale agriculture and horticulture.

With a changing climate expected to increase irrigation demand (Weatherhead and Knox, 2015; Rodriguez Diaz et al., 2007; Else and Atkinson, 2010) and the frequency and severity of droughts also expected to impact on irrigated agriculture (Fowler and Kilsby, 2004), this study builds on previous research (Morris et al., 1997; Knox et al., 2000) to provide the first comprehensive national spatial assessment of the financial benefits of supplementary irrigation, both in terms of yield and quality assurance in a dry year. This will support policies to better understand the impacts of abstraction restrictions in the sector, and to improve drought management strategies which balance impacts across different economic and environmental sectors. As a result, the farming community will be better equipped to estimate potential losses arising from drought, as will governments and agencies in deciding where and when to impose restrictions on agriculture with minimum economic impact. The analysis is applied to outdoor irrigated cropping in England and Wales, but the approach is applicable in other countries where appropriate datasets are available. The methodology and outputs also have significant implications for the implementation of abstraction controls within the Water Framework Directive (WFD).

2. Material and methods

In summary, a four staged approach was developed:

1. Deriving and mapping agroclimate variability using potential soil moisture deficit (PSMD) as an aridity indicator;
2. Modelling and mapping theoretical volumetric irrigation water demand for the major irrigated crop categories during a design dry year;
3. Mapping the financial value of supplemental irrigation, by crop category and per unit of water applied (water productivity), and;
4. Conducting a sensitivity analysis to assess how the irrigation benefits might change under contrasting agroclimate, market (price) and water supply (water price) conditions.

A brief description of each stage is given below.

2.1. Mapping agroclimate variability

A dry year in England and Wales in irrigation terms is typically characterised by periods of low rainfall and high evapotranspiration (ET) from June to August (Weatherhead et al., 1997). The combined effects of rainfall and ET on irrigation demand can be reflected via an aridity index using potential soil moisture deficit (PSMD). The advantage of using PSMD over other agroclimatic indicators (e.g. Standardised Precipitation Index, SPI) is that the distribution of rainfall and ET throughout the year is taken into account. It can also be used to identify the dryness or wetness of a specific location for a given year. The index has been widely used internationally to quantify irrigation needs at different scales and assess climate impacts on water demand (Knox et al., 1997, 2010a,b; De Silva et al., 2007; Rodríguez Díaz et al., 2007). It is also used by the regulatory authority in England and Wales for setting licences (permits) for irrigation abstraction (Rees et al., 2003). In this study, the PSMD index for 2010 was calculated using a 5 km × 5 km gridded monthly climatic dataset from the UK Meteorological Office derived from observed historical weather data collected from a range of meteorological stations spatially distributed across the UK (Perry and Hollis, 2004). The rationale for using 2010 data was twofold: Knox et al. (2014) reported that 2010 closely approximated to a 'design' dry year in irrigation terms (statistically defined as the unconstrained water demand with an 80% probability of non-exceedance); secondly, national irrigated area data were available from the most recent 2010 Defra Irrigation Survey (Defra, 2011).

Reference evapotranspiration (ETo) was calculated using the gridded monthly temperature, solar radiation, wind speed and relative humidity data and the FAO Penman-Monteith combination equation (Allen et al., 1998). Using monthly rainfall (P_t) and reference evapotranspiration (ETo_t) data, the PSMD (mm) for each month (t) is calculated as following:

$$PSMD_t = PSMD_{t-1} + ETo_t - P_t \tag{1}$$

In months where $P_t > (PSMD_{t-1} + ET_{ot})$, any initial soil moisture deficit is filled and hence $PSMD_t = 0$. In the UK, soil moisture deficits typically start to build up in early spring as ET > P, peak in mid-summer (July–August) and then decline to zero through autumn and winter as P > ET. Therefore in the UK, the estimation of PSMD can start with January as month $t = 1$. The maximum PSMD of the 12 months of each year is the PSMD_{max} value assigned to that year at that location. A map showing the spatial variation in PSMD_{max} for England and Wales at 5 km grid resolution for 2010 was produced and then used to estimate volumetric irrigation demand.

2.2. *Mapping theoretical volumetric irrigation demand (m^3)*

The spatial volumetric irrigation needs of the main outdoor crop categories in England and Wales were derived by applying the methodology developed by Knox et al. (1997) to spatial datasets of climate, soil type, crop areas and irrigation survey results. In summary, Knox et al. (1997) used a daily time-step water balance model (Hess, 1996) to calculate the theoretical unconstrained annual irrigation need (mm) for each of the major irrigated crop categories (potatoes, field vegetables, sugar beet, soft fruit, orchard fruit, grass, and cereals) grown on a contrasting range of soil types at agroclimatically contrasting locations. These results were then correlated using linear regression analyses against the PSMD_{max}. Knox et al. (1997) developed formulae for each crop relating the theoretical irrigation need for any specific year or location to soil type and agroclimate (PSMD_{max}).

The spatial volumetric water demand in a grid square was calculated by applying the regression relationships derived by Knox et al. (1997) for each crop type to the gridded agroclimate dataset (PSMD_{max}) for 2010, taking account the spatial distribution of soil types from the National Soil Map[1] and estimated irrigated area (ha) in each grid pixel. The irrigated area within each catchment was calculated using a GIS by applying the 2005 and 2010 Defra Irrigation Survey results to the 2 km × 2 km gridded land use dataset derived from the Defra, 2011 June Agricultural Census data. Three different soil types were considered for calculating theoretical water demand, depending on available water capacity (AWC): low AWC (<100 mm/m), medium AWC (100–175 mm/m), and high AWC (>175 mm/m).

2.3. *Mapping the financial value of supplemental irrigation (£/m^3)*

The positive effect that irrigation has on crops, both in terms of yield and quality (and therefore revenue) (Weatherhead et al., 1997) is crop specific since each crop responds differently to the same volume of water applied. Several studies have estimated the yield response to irrigation (e.g. Morris et al., 1997; based on experimental data and farm records) allowing us to estimate the average net yield increase for each unit (mm) of water applied (Table 1). This is then up-scaled to estimate the net yield increase in each grid pixel according to the theoretical irrigation need (based on the local soil type and PSMD_{max}). However, irrigation also has a very important effect on quality which is critical for some crops; for example, on potatoes it is used to limit the incidence of common scab (*Streptomyces scabies* spp.) which causes skin imperfections or for lettuces where water shortages can negatively impact on size, shape and leaf defects. Irrigation is also essential for soft fruit (strawberries) since the majority of the crop is grown under temporary polytunnels to prevent rain damage and thus attain Grade 1 class fruit, which has a much higher price than the strawberries sold for processing. In this study, we estimated the benefits of irrigation on crop quality, expressed as a percentage increase in crop price (£/t) based on published literature corroborated by farmer interviews. These data have been used to derive estimates of the quality benefits of irrigation for each crop and soil type (Table 2). All costs and prices used in this assessment, including the additional costs due to increased production shown as in Table 1 were checked and confirmed with horticultural and soft fruit growers via a series of face-to-face interviews in 2015.

Table 1
Main economic data and crop yield response to irrigation.

Crop category	Crop price[a] (£/t)	Additional costs due to increased production (% gross benefit)[b]	Average crop yield response per hectare[c] (t/mm)
Early potatoes	155	15%	0.08
Main crop potatoes	104	15%	0.08
Cereals (wheat)	110	3%	0.02
Sugar beet	31	10%	0.13
Vegetables (carrots)	95	15%	0.13
Soft fruit (strawberries)	600	25%	0.03
Grass- graze	95	0%	0.03
Grass- silage	95	22%	0.03
Orchard fruit (dessert apple)	479	25%	0.02

[a] These represent the average national crop price (£/tonne, adjusted for inflation using the Agricultural Price Index for the UK, which measures the monthly price changes in agricultural outputs and inputs for all major crops). Information was collected for all crop categories over the past three drought episodes in the UK (2003, 2004–2006, 2010–2012), from the relevant years of the Farm Business Survey (e.g. Defra 2005), the Agriculture in the English regions (e.g. Defra 2006) and the Farm Management Pocketbook (e.g. Nix, 2010).

[b] Extra costs associated with the additional production due to irrigation. These include: additional harvesting, handling, drying and if relevant, direct packaging and marketing costs (Morris et al., 1997), but not the variable costs of irrigation.

[c] Average yield response to irrigation, normalised by irrigation depth, obtained from previous experimental data and field experience in the UK from Morris et al. (1997). A simplifying assumption of a linear relationship between irrigation depth and yield is used to estimate irrigation benefits, given the impracticability of calibrating biophysical crop models to characterise the non-linear response for all combinations of agroclimate, soils and crop type across the UK.

Table 2
Crop quality benefit arising from irrigation for different available water capacity (AWC) soils, expressed as% increase in the rain-fed crop price.

Quality premium (% increase in price)			
Crop category	Soil AWC		
	High	Medium	Low
Early potatoes	11%	23%	40%
Main crop potatoes	25%	30%	40%
Cereals (wheat)	0%	0%	5%
Sugar beet	0%	0%	5%
Vegetables (carrots)	6%	15%	30%
Soft fruit (strawberries)[a]		429%	429%
Grass	0%	0%	5%
Orchard fruit (dessert apple)	14%	20%	25%

[a] The very large price benefit due to irrigation for strawberries reflects the difference in price between Class 1 strawberries (that can only be achieved with irrigation, and have an average price of £3150 per tonne) and the lower quality strawberries that result if growers are unable to meet crop water requirements in a dry year (and sold for processing at an average price of £600 per tonne.

Conventionally, it is assumed that crop prices rise during a drought as agricultural production is affected by weather conditions (FAO et al., 2011). However, the final impact on price is influenced by many other factors, such as the timing and onset of the drought, world market prices and the extent to which imported products affect the local domestic food market. Thus, in estimating the benefits of irrigation in financial terms, the average crop price (£/tonne, adjusted for inflation using the government Agricultural Price Index for the UK) over the past three drought episodes in the UK (2003, 2004–2006, 2010–2012) were used (Table 1). Regionally disaggregated price information is available for some crop types, but not all; we therefore assumed national average crop prices for our analysis, having checked that differences were not significant across the country for the available price data (for instance, the price of cereals has a coefficient of variation (CV) across regions <0.05 cereals and <0.16 for potatoes). Price data for these periods

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[1] http://www.landis.org.uk/data/natmap.cfm.

were drawn from various sources including Defra (2005, 2006); Nix (2010).[2]

For each crop, the additional costs associated with the increased production (e.g. during harvest, handling, drying) (Table 1) were deducted from the gross benefit. The variable irrigation costs (repairs, fuel, labour and machinery, water charges) were also deducted. The costs of irrigation vary considerably depending on local circumstances, the type of irrigation system, the water source and crop water requirements (Morris et al., 2014). For calculation purposes, we assumed average variable costs of irrigation in the UK (1.50 £/ha mm, based on Nix (2010)).

By combining the yield and quality benefits, the total financial benefit of supplemental irrigation can be estimated. Here, we consider only the extra net benefits derived from irrigation in comparison with the benefits that the farmer would get from the same crops grown under non-irrigated conditions (the counter-factual); i.e. the added value associated with irrigation relative to rainfed production.[3] Fig. 1 shows that the yield and quality benefits are multiplicative, not additive, as the quality premia are relevant to the whole crop not just the yield increase. From the gross benefits illustrated in Fig. 1, the irrigation costs and additional costs associated with higher levels of production must be deducted to obtain the net extra margin (£/ha mm) derived from supplemental irrigation.

The following equations were derived and used to estimate the net irrigation benefit (total and per ha) and water productivity (£/m^3) for each grid pixel (i):

- Total irrigation benefit (£)

$$B_i = \sum_{c=1}^{n}\sum_{s=1}^{m}[((Y_{c,s} + Q_{c,s} - P_c - I) - R_{c,s}) * A_{c,s}] \tag{2}$$

- Benefit per irrigated hectare (£/ha)

$$B_i^{ha} = B_i/A_{c,s} \tag{3}$$

- Water productivity (£/m^3)

$$W_i = \sum_{c=1}^{n}\sum_{s=1}^{m} B_i/V_{c,s} \tag{4}$$

where, B is the financial irrigation benefit (£). Y refers to the yield benefit derived from irrigation (£/ha) and Q the quality benefit (£/ha). P represents the extra crop costs (£/ha) and I the irrigation costs (£/ha). R represents the total benefit associated with non-irrigated production (£/ha). Subscript c represents each of the eight major irrigated crops (namely, early potatoes, maincrop potatoes, cereals, sugar beet, vegetables, soft fruit, grass, and orchard fruit); subscript s denotes the soil available water capacity (AWC) (high AWC, medium AWC and low AWC). A is the irrigated area of each crop (ha); W is the water average productivity (£/m^3) and V is the theoretical irrigation water demand (m^3).

2.4. Sensitivity analysis

For each crop category, agroclimate (PSMD), crop price and water cost were assumed to have the greatest impact on irrigation benefit. Higher PSMD values imply higher irrigation needs (mm), and thus higher benefits derived from fulfilling crop water requirements, as the differences between rainfed and irrigated yield would be higher (Morris et al., 2014). Higher crop prices increase the benefit that irrigators derive from each incremental depth of water applied (mm) to their crops. Costs of water will have a direct impact on water productivity (£/m^3). Using different agroclimate and price scenario, a sensitivity analysis was also undertaken to assess how the irrigation benefits might be impacted by changes in each of these variables.

3. Results

3.1. Irrigated production and water resource availability

Fig. 2a shows the spatial variability in agroclimate across England and Wales for 2010, assumed here to represent a 'design' dry year, defined as a year with an 80% probability of non-exceedance. The areas of highest aridity (high PSMD$_{\max}$) are concentrated in eastern and southern England, notably in Norfolk, Suffolk, Essex and Kent. These correspond to parts of the country where irrigated cropping is most concentrated (Fig. 2b) reflecting suitable soils and agroclimatic conditions for potato and field-vegetable production in East Anglia, and soft and orchard fruit production in Kent. The location of irrigated production is also closely correlated with (though not necessarily the cause of) water resources availability with 59% located in either over-licensed and/or over-abstracted catchments (Fig. 2c). In contrast, regions with the lowest aridity extend across much of Wales, the south west and north-west of England, reflecting higher rainfall and less suited land for intensive irrigated vegetable production. In these regions, rainfed production including extensive grassland for livestock is the dominant form of agricultural land use.

3.2. Irrigation water demand, value and productivity

The calculated spatial distribution of volumetric irrigation demand in England and Wales is shown in Fig. 3a. Nationally, the majority (80%) of irrigation demand is concentrated in central and eastern England, notably in EA Anglian (130×10^6 m^3) and EA Midlands (30×10^6 m^3) regions. The total volumetric demand in 2010 ('design dry year') was estimated to be 200×10^6 m^3. Maincrop potatoes and vegetables have the highest irrigation demand, representing 56% and 23% of total theoretical water demand, respectively.

The financial benefit of irrigated production in 2010 was estimated to be £665 million. As shown in Fig. 3b, the highest benefits accrue in Anglian, Midlands and Southern EA regions, where high-value crops (soft fruit, potatoes and vegetables) are concentrated. Soft and orchard fruit has the highest average benefit per hectare (Table 3) with most production concentrated in EA Anglian and Southern regions. Maincrop potatoes are also an important irrigated crop in EA Anglian region, representing a significant proportion of total benefits in that area (close to 34%). Areas with lower irrigation benefits reflect areas where grassland and cereals dominate the land use mix. Based on the coefficients of variation (cv), it can be deduced that the spatial variability in irrigation benefits is very high for cereals and very low for maincrop potatoes and orchard and soft fruit (as these crops benefit from irrigation for quality assurance in almost all areas).

As discussed earlier, the total irrigation benefit is a combination of both yield and quality benefits which differ between individual crop types. Table 4 shows the relative contribution of each component to the total irrigation benefit for each crop. The irrigation benefits associated with quality assurance are higher than the yield benefits for soft fruit, maincrop and early potatoes. For example,

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[2] These sources were consulted for the following years: 2003, 2004–2006, 2010–2012. Only an example of each is shown in the References (Defra, 2005; Defra 2006; Nix 2010).

[3] Fixed costs were not considered as we are studying the economic importance of irrigation in a dry year; a farmer has to cover those costs every year irrespective of whether they irrigate or not. We therefore only considered the extra benefits and extra costs of irrigation.

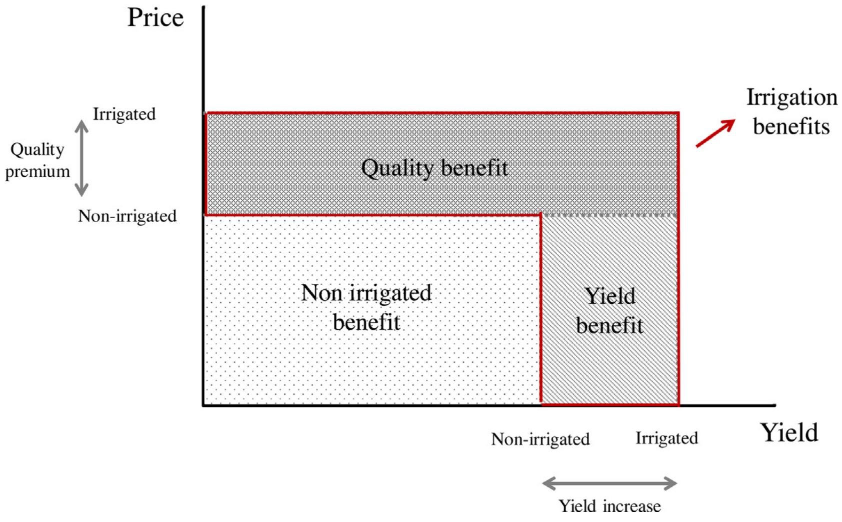
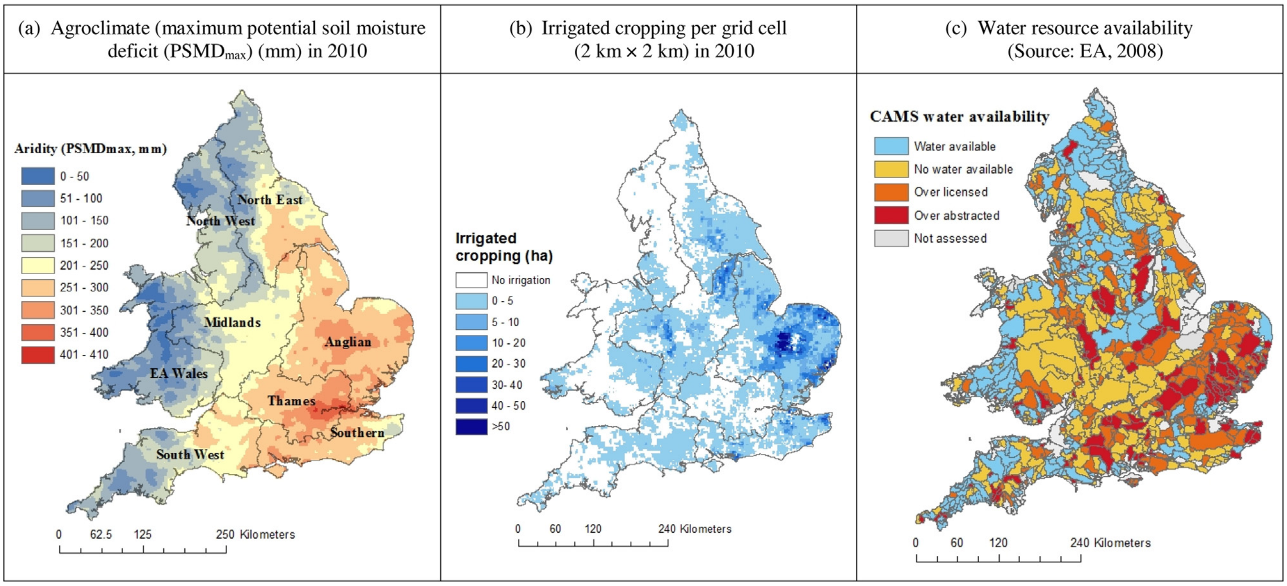


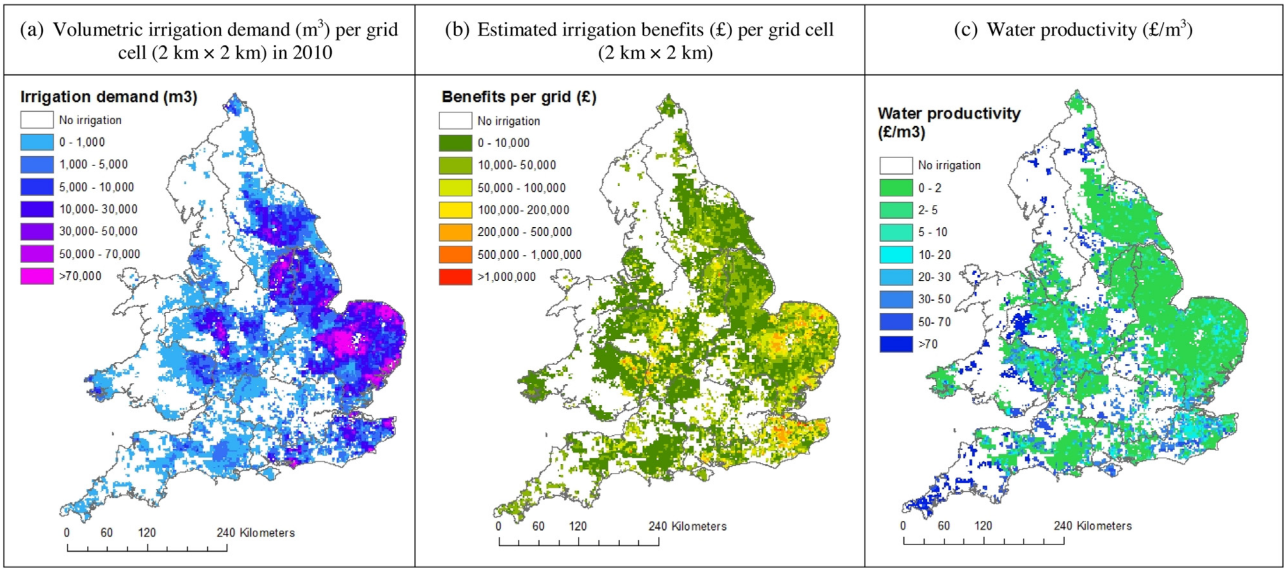
Fig. 1. Conceptual representation of the crop quality and yield benefits attributable to supplemental irrigation.


(a) Agroclimate (maximum potential soil moisture deficit ($PSMD_{max}$) (mm) in 2010

(b) Irrigated cropping per grid cell (2 km × 2 km) in 2010

(c) Water resource availability (Source: EA, 2008)

Fig. 2. Maximum potential soil moisture deficit ($PSMD_{max}$) (mm) (a); irrigated cropping (ha) (b); and EA water resource availability(c) for England and Wales, by EA region.


(a) Volumetric irrigation demand (m^3) per grid cell (2 km × 2 km) in 2010

(b) Estimated irrigation benefits (£) per grid cell (2 km × 2 km)

(c) Water productivity (£/m^3)

Fig. 3. Volumetric irrigation demand (m^3), estimated irrigation benefit (£) and water productivity (£/m^3) for England and Wales, by EA region.

Table 3
Irrigated area and estimated combined yield and quality benefits from irrigation by crop category across England and Wales in the design dry year.

Crop	Irrigated area (ha)	Total benefits (£million)	Average benefit per ha (£/ha)	Standard deviation	Coefficient of variation
Early potatoes	3794	6.36	1,680	388.03	0.23
Maincrop potatoes	31,064	127.47	3919	581.11	0.15
Cereals	9,563	0.14	15	18.94	1.27
Sugar beet	5,898	3.55	598	130.73	0.22
Vegetables	18,413	60.98	3110	1,432.58	0.46
Soft fruit	9297	461.50	54,973	2,236.25	0.04
Grass	3,315	0.87	255	64.45	0.25
Orchard fruit	1,057	4.48	8,834	1,294.41	0.15

Table 4
Estimated average contribution of yield and quality benefits (%) to overall irrigation benefit, by crop category in England and Wales.

Crop category	Yield contribution to total benefits (%)	Quality contribution to total benefits (%)
Early potatoes	47	53
Maincrop potatoes	49	51
Cereals	77	23
Sugar beet	96	4
Vegetables	69	31
Soft fruit	3	97
Grass	96	4
Orchard fruit	65	35

more than 60% of the total benefit derived from irrigating vegetables in a dry year is derived from an improvement in quality. For other crops, such as grass, sugar beet and cereals, which have a much higher tolerance to drought and are not part of the fresh produce supply chain, most of the irrigation benefits are related to a yield increment with irrigation having a relatively low impact on quality. The proportion of irrigation benefits derived from quality improvements are also higher on low moisture retentive (AWC) soils (Table 2).

Fig. 3c shows the spatial distribution of benefits per unit of water applied (£/m^3) or water productivity for the composition of land use in 2010. The most productive areas are mainly in the south-east and around the Bristol Channel (south and west) and in the midlands. The data for individual crop types shows soft fruit and early potatoes have the highest average water productivity (£52 and £1.94 per m^3, respectively), with cereals (£0.08 per m^3) and grass (£0.11 per m^3) having the lowest values. Irrigation benefits tend to be highest for high-value (£/ha) crops, where irrigation can make most difference to yield and farm-gate price; and for crops that are associated with relatively high capital and labour production costs, helping to secure their viability. That is the case for strawberry production in the UK. The areas showing the highest water productivity (>£50 per m^3) correspond to land where soft fruit is the only crop being irrigated. Expressing net benefits per unit of irrigation in this way, however, attributes all net benefits of crop production to the irrigation activity, rather than sharing it amongst the various components of investment, on the understanding that irrigation is an essential, non-substitutable component of production. These high returns to water are indicative of the essential nature of irrigation in England and Wales, where water adds most value in relatively intensive high-value, high-risk production systems.

3.3. Sensitivity analysis

Sensitivity analysis can provide an insight into the impact that changes in agroclimate, crop price or irrigation costs can have on irrigation benefits. As mentioned, PSMD was used in this study as an agroclimate index. Fig. 4 shows the financial value of irrigated agriculture in England and Wales, for different agroclimate and crop price scenario. In a very dry year,[4] with very high crop prices[5] the total economic value of supplemental irrigation could reach almost £1130 million, assuming that crop irrigation needs are fully met. Cereals, grass and sugar beet are most sensitive (in terms of a percentage change in, albeit low, irrigation benefits) to a change in PSMD, with strawberries and early potatoes being least sensitive (Fig. 5). However, it should be highlighted that Figs. 5 and 6 show the 'relative' changes, so for instance for cereals an increase of 148% in average benefit represents only £17/ha. Fig. 6 summarises the effects of changes in farm gate commodity prices on irrigation benefits. The analysis shows, for example, that if the price of cereals were to increase by 10% then the irrigation benefits would increase by nearly 40%.

If water resources become more scarce in future, then the water charges (£/m^3) for agricultural abstraction are likely to increase, with the aim of reducing water use and improving irrigation efficiency. A change in water price will affect the benefits from supplemental irrigation and hence water productivity. Fig. 7 shows the estimated change in water productivity (%) caused by a change in the cost of irrigation water for farmers in different regions. Changes in water costs have an important impact on water productivity, although they may not be significant depending on the crop mix. For example, a 50% increase in water costs would reduce water productivity (£/m^3) by <2%. In those regions with a large proportion of high-value crops such as soft fruit and vegetables, the impact of an increase in water price will be lower, as our results demonstrate. Although current water charges represent a small percentage of the average total crop cost per hectare, if water prices were to increase, then the viability of irrigating some of the least-profitable crops (grass and cereals) would be further reduced.

4. Discussion

4.1. Implications for water management

This study represents the first international attempt to develop a national assessment of the financial benefits of supplemental irrigation for a defined dry year, compared to rainfed cropping, taking account of the spatial distribution of irrigated crops, and the factors that influence irrigation demand. For the eight crops examined, the highest irrigation benefit is for soft fruit (strawberries) and orchard fruit (dessert apples); and the lowest is for cereals due to the high differential in price between the crops, although differences across regions are also considerable. Our estimate of irrigation demand in EA Anglian Region is marginally higher (130×10^6 m^3) compared to that (104×10^6 m^3) estimated by Knox et al. (2000). However, our

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[4] The driest scenario was defined based on the highest PSMD$_{max}$ difference between 2010 and the most severe drought episode in the UK, 1976. According to Knox et al. (2014), this difference in South Wales and South West England was close to 100%.

[5] Price range based on the crop prices in the UK during the past drought episodes (2003, 2004–2006, 2010–2012).

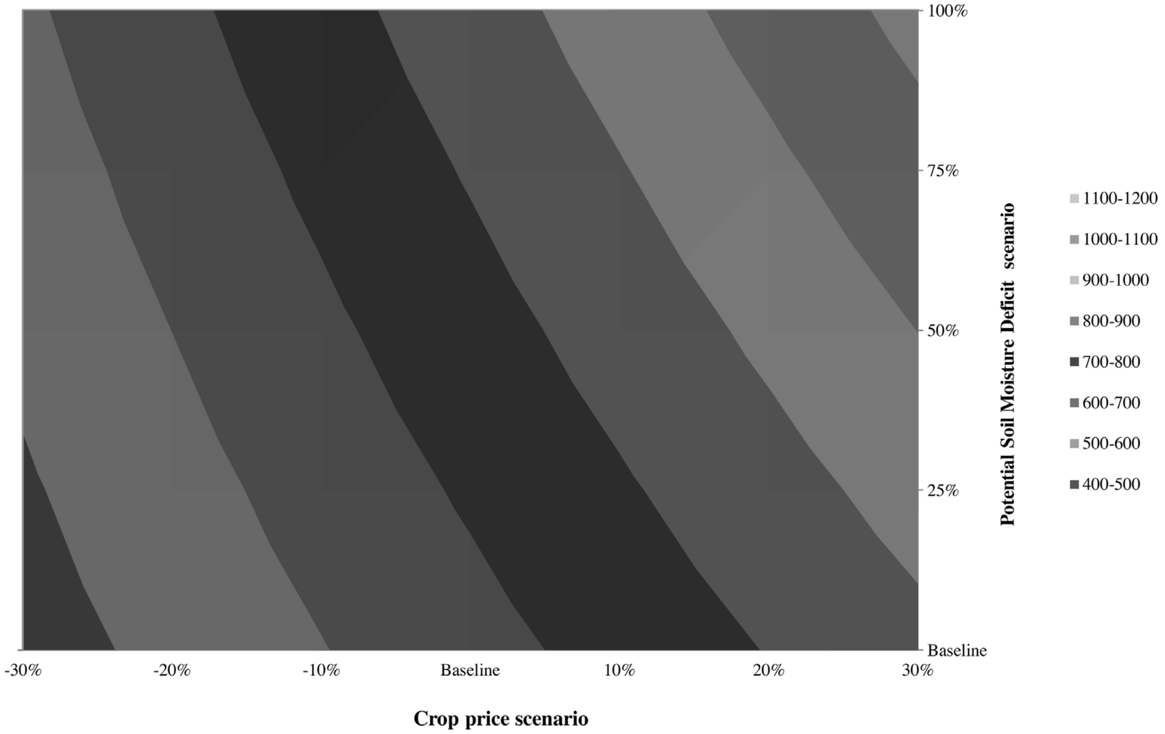

Fig. 4. Estimated financial benefit (£ million) of supplemental irrigation in England and Wales under different agroclimate (PSMD) and crop price scenario.

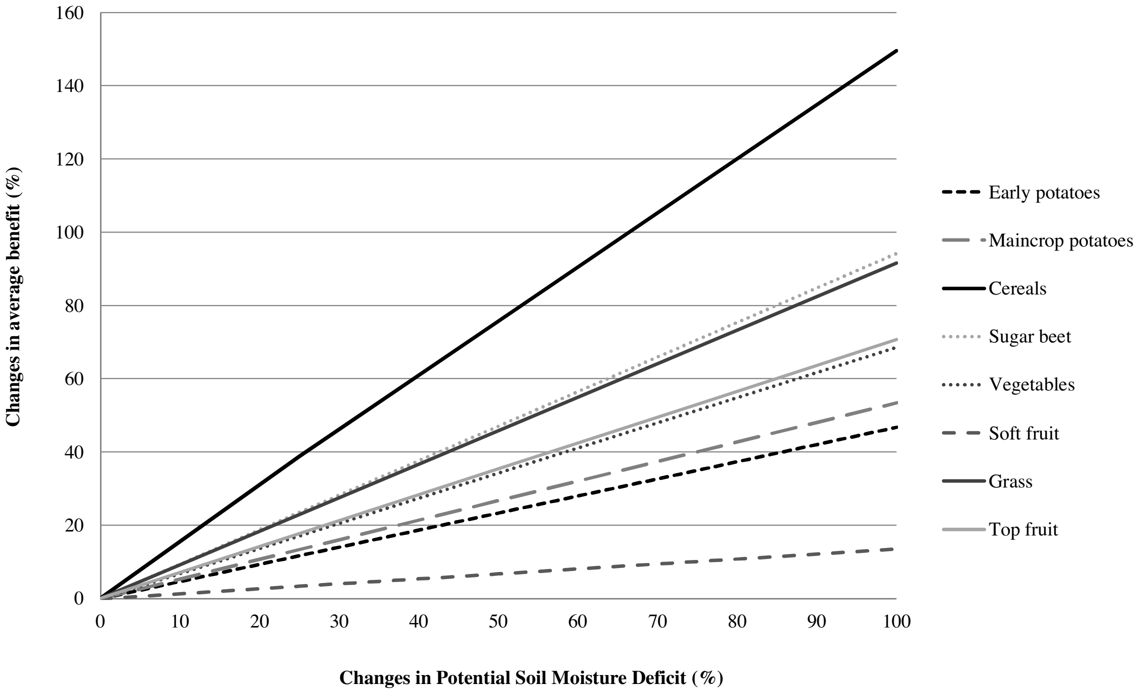

Fig. 5. Estimated change (%) in average irrigation benefit for selected agroclimate ($PSMD_{max}$) scenario.

results for the average benefit (£/ha) of irrigated maincrop potatoes are consistent with those reported by Morris et al. (2014).

Since the work carried out by Morris et al. (1997); Knox et al. (2000), irrigated agriculture and demand for water has changed markedly (Weatherhead et al., 2015). This is partly due to the changes in cropped area and crop mix over the last decade together with changes in abstraction licensing and water allocation. Irrigation has become increasingly concentrated on fewer high-value crops; coupled with improvements in application technology scheduling and in-field management. The rising real cost of abstracted water and energy for pumping has also led to a reduction in irrigation on some crops where the benefits of irrigation were previously marginal, notably grass and sugar beet. At a national scale, Defra (2011) reported that the total irrigated area in England and Wales has decreased by 43.5% from 2001 to 2010, yet the benefit has increased

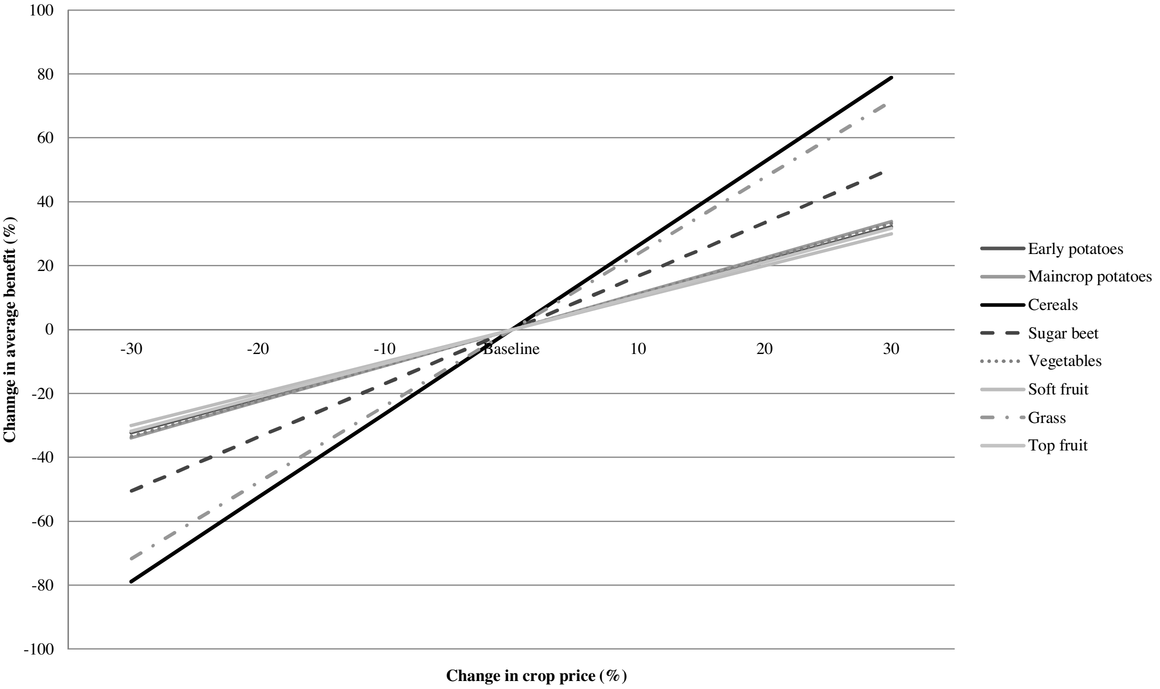

Fig. 6. Estimated changes (%) in average benefit by crop due to a change in crop price.

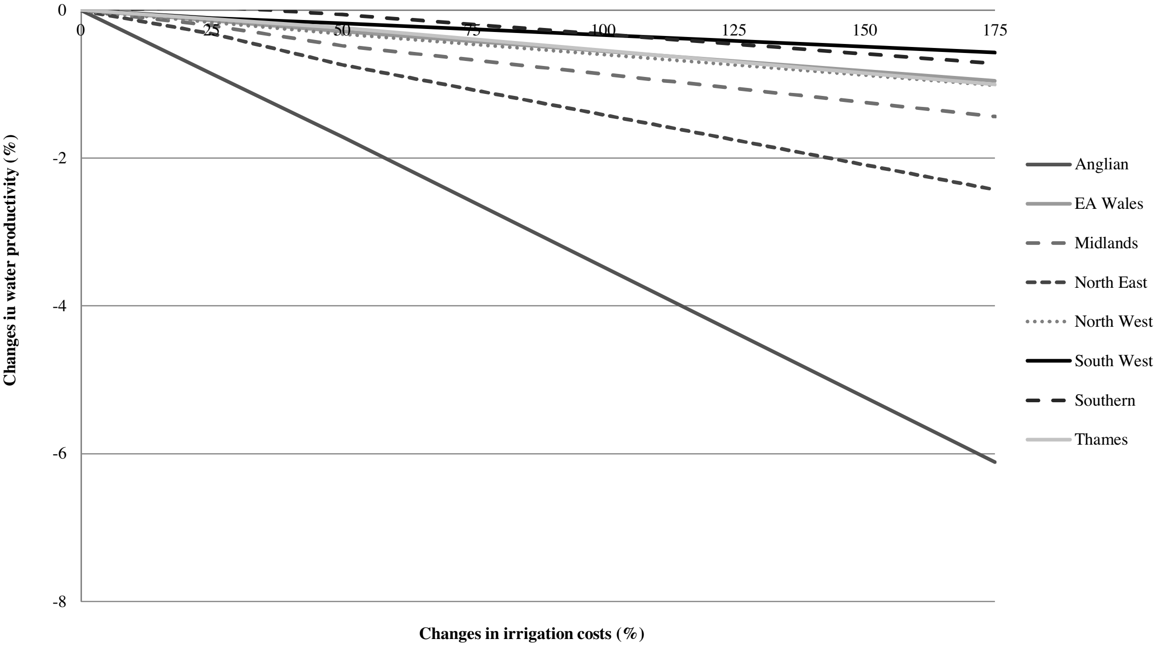

Fig. 7. Estimated change in average water productivity (%) due to an increase in water cost.

In future it is likely that the frequency and severity of droughts in the UK will increase, potentially leading to an increase in crop water requirements. It is likely that irrigation will become more important but also more challenging, as there will be a greater probability of low water availability periods that will affect irrigators, since most agricultural production is concentrated in catchments that are already water stressed. Irrigated agriculture could lose its comparative advantage if constrained, unless the sector adapted to changing water availability. The economic rationale for irrigation is to secure water to add value, particularly through quality assurance, in areas that have comparative advantage for crop production. Many of these areas are in water deficit: thus there is an emerging 'critical irrigation geography' with competing demands between water for irrigation and other uses. During drought conditions, irrigated agriculture is potentially exposed because of its greater dependency on water, with unintended outcomes and consequences. Irrigation may not help in severe drought conditions, unless drought responses for agriculture are explicitly 'designed' into farm irrigation plans and regional drought management strategies.

According to the analyses presented here, the inability to irrigate in future dry years could lead to severe economic impacts for the farming community. Thus, to de-risk their businesses, a combination of irrigation with other drought management strategies will be essential. In recent decades farmers in the UK have invested in irrigation management to cope with a more uncertain water supplies, including for example, building on-farm water storage reservoirs, investing in more efficient technologies or creating water abstractor groups (Holman and Trawick, 2011; NFU 2015). In areas where increased irrigation from direct summer abstraction is not a viable option for coping with drought, other measures will need to be implemented, such as the selection of more drought-resistant varieties (Pidgeon et al., 2006) or changes in planting programmes to avoid late summer maturation (Wreford and Adger, 2010). These adaptation strategies would thus help reduce the potential losses in years when irrigation water was constrained.

In England, irrigation constitutes only 4% of the total cropped area, yet it represents 20% of crop value (EA, 2008). In a dry year, the contribution of irrigated agriculture to the total crop value could be much higher. The benefits derived from irrigation vary spatially in England and Wales. Thus, the magnitude of drought impacts on these benefits will differ depending on which areas of the country are most affected. In a very dry year, as our sensitivity analysis suggests, some crops will be more affected (in terms of financial benefits) than others by an increase in aridity (PSMD). The results from this analysis could help guide water management decisions by regulatory authorities to minimize the overall economic impact of restrictions on water abstractions, changes in the abstraction licensing system and WFD implementation. This includes consideration of the economic impact on incomes, employment and livelihoods in the farm sector, the food and allied industries and other parts of the rural economy where irrigation is important. This wider perspective would also consider regional and national food supply and security issues placed under pressure during drought conditions, as well as the impacts of agricultural water abstraction on the environment. Apart from the potential impacts of abstraction restrictions on the financial benefits of irrigation highlighted in this paper, the water regulatory agency should also take into account the positive and negative externalities (i.e., more water for the environment vs. irrigated agriculture profitability, rural employment and food security), that imposing abstraction restrictions could have on the different water users and the environment.

4.2. Methodological limitations

Finally, this work has some inherent limitations that should be recognised. The study by Morris et al. (1997) was applied to a specific area (Anglian region) where most irrigation is concentrated. Although some of the data used in this study have been updated, our analysis is informed by their results, which might cause errors in the estimation of the financial benefits of irrigation for other regions in England and Wales. Our assumption regarding the relationship between irrigation and crop quality could be improved by developing an irrigation- related quality indicator that could better explain variations in market price. The assumption of a linear relationship between irrigation depth and yield is considered the most feasible option to estimate irrigation benefits for most of the crops in this study, given the difficulty in calibrating biophysical crop models to simulate farm yields for all combinations of agroclimate, soils and crop type. However, it is also probably the greatest source of uncertainty given the assumption of linearity over the 'relevant range' of irrigation water use. Another potential source of error relates to the assumptions on irrigation cost. Although in England and Wales different irrigation systems and water sources (with different associated costs) exist, we assumed the costs associated with direct abstraction from a surface water (river, stream) and overhead application using a hose reel fitted with a gun (93% of the total irrigated area used hose reels in 2010 according to Defra (2011)). However, we recognise that other water sources are used, including groundwater and storage reservoirs which would change the structure of irrigation costs. Finally, we used 'representative' irrigated crops for some crop categories (i.e. carrots for vegetables, wheat for cereals, strawberries for soft fruit, apples for orchard fruit) which could introduce some uncertainty into our estimates. We also assumed that the counterfactual for irrigated crops would be the rainfed equivalent, which is reasonable as we are considering the costs of unexpected droughts or restrictions. However, the counterfactual in areas of highest irrigation needs is likely to be wheat or barley, rather than a rainfed equivalent of the irrigated crop. Finally, the financial assessment has not considered the economic impacts of crop switching due to, for example, changes in future land suitability and/or agroclimate conditions. Further primary data collection could help address the limitations outlined since most are related to constraints in farm level data availability.

5. Conclusions

Drought episodes can severely impact on agricultural production in the UK, and are projected to become more frequent and extreme. This work presents a methodology to assess the geospatial financial benefits of supplemental irrigation in England and Wales. Despite the fact that many crops grown in the UK are rainfed, our analyses highlight the importance of supplemental irrigation to achieve yield and quality assurance to guarantee profitable crop production in dry years. In a future drier climate with greater aridity, irrigation would only become more crucial to buffer the impacts of the capricious nature of rainfall. Information arising from this work could support water resource planning and decision making to reduce the impacts of low flows on agriculture during drought periods. The procedure developed here could readily be applied to other crop types and/or mixes in other agroclimatic regions worldwide.

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