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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:

$$PSMD_t = PSMD_{t-1} + ETo_t - P_t \quad (1)$$

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