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Assessing sustainability of winter wheat production under climate change scenarios in a humid climate — An integrated modelling framework

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ABSTRACT

The proposed study draws a novel framework to assess the sustainability of winter wheat under climate change conditions and irrigation as an adaption measure to reduce yield variability. The methodology combines outputs from a general circulation model (GCM), the Food and Agriculture Organization's (FAO) crop growth model (AquaCrop), a life cycle assessment (LCA) model and economic modelling. Long-term observed climate data (1970–1991) collected in Cambridge (Cambridgeshire, UK) were used to downscale the projected climate data from the GCM for 2050. The structural characteristics of the case study are representative of a typical farm in this UK region. A six-year average wheat price (2007–2012) was considered and the irrigation costs for the economic model were calculated assuming the market prices in 2014. Sensitivity analysis assessed in the longer term included the expected variations due to the increase in world wheat prices and the energy costs.

The direct impacts of climate change on winter wheat grown in the East of England, would be a reduction in the rainfed yield (between −5.4% and −32.9%), stronger under the low emission scenario (B1). The projected economic losses from rainfed winter wheat production are expected to range between −43.6% and −100.0%. Irrigation could in the future be an adaptation measure for yield increase (10.5% to 64.3%), lower under B1 and to improve the financial appraisal of irrigation investment which would raise between 41 and 429 £ ha^{-1}. However, negative externalities are exacerbating pressures on air and water resources; an increase in irrigation water requirements between 25.0% and 39.1% increases global warming potential between 20.4% and 28.3%. Environmental indicators under scenario B1 performed better than the high emission scenario (A1). Finally, under future climate scenarios, the results confirmed that irrigated winter wheat grown on lighter soils using hose reel sprinkler systems fitted with a boom, is more sustainable than that grown on heavier soils using hose reel sprinkler systems fitted with a raingun.

1. Introduction

Climate change is unavoidable (Matthews and Caldeira, 2008; Weaver et al., 2007), and the biggest impacts of climate warming are likely to affect the sustainability of agricultural and food systems. Both are highly vulnerable to continuously changing climatic patterns (IPCC, 2007). These impacts are expected to further decrease world crop yields (Parry et al., 2004). However, climate change impacts at regional level would have more heterogeneous results (Lehmann et al., 2013).

So, frequent consideration is given to adaptation measures that moderate negative impacts, reduce crops' vulnerability to dangerous climate changes and, hence, decrease world food insecurity (IPCC, 2007). Modifications such as changing crop varieties and/or planting dates, may have positive impacts at relatively low costs (Lehmann et al., 2011; Torriani et al., 2007). However, such adaptations at regional level have greater dependency on the local socio-economic and agronomic conditions that are often ignored in literature addressing the vulnerability of agriculture to climate change (e.g. Mushtaq et al., 2013; Reidsma et al., 2010).

The literature indicates that substantial benefits will most probably result from costly measures such as the development of new varieties and irrigation (Rosenzweig and Parry, 1994). Yet, what sometimes appears to be an effective climate change adaptation measure may actually jeopardise the fundamental pillars of sustainable development i.e. the social, economic and environmental dimensions. This highlights the need for sustainable adaptation measures and strategies (Eriksen and O'Brien, 2007) and has also been emphasised by Röder et al. (2014) who showed, through a life cycle assessment (LCA), that UK wheat production would increase greenhouse gas emissions by 26% in order to meet future demands under climate change scenarios.

Wheat is one of the most important staples in the world and is grown on more land area than any other commercial crop. With a cultivation range extending from Russia to the tropics and sub-tropics (Feldman, 1995), wheat provides food for humans and livestock

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(Shewry, 2009; FAO, 2002) and has a high adaptability characteristic to different conditions (climate, soil, management). Grown largely as a rainfed crop in many areas of the world (e.g. temperate climates, subtropics with winter rainfall, highlands) irrigation is required in some areas (e.g. sub-tropics with summer rainfall) (FAO, 2013a).

The impacts of climate warming on wheat at global and regional scales have been abundantly assessed, but the conclusions drawn are conflicting. Parry et al. (2004) statistically derived agroclimatic regional yield transfer functions from site-level results under different Special Report on Emission Scenarios (SRES). They showed that a number of cereal crops (wheat, rice, maize and soybean), wheat in particular, was subject to potential yield changes at global level, which could expose global food security to high risks and consequences (Barnett, 2003). In contrast, a meta-analysis by Wilcox and Makowski (2014) contradicted the previous results by showing that the effects of high CO_2 concentrations would outweigh the effects of increasing temperature and declining precipitation, leading to increased wheat yields depending on the geographical location. Differing again, Supit et al. (2012) used the Crop Growth Monitoring System and outputs from three general circulation models in combination with a weather generator to demonstrate that whilst crops planted in autumn and winter, such as winter wheat in Europe, might benefit from the increasing CO_2 concentration in the short run, a lesser CO_2 increase might lead to declining or stagnant yields after 2050. In a review evaluating the interactions of climate change impacts on water and agriculture in Europe, Falloon and Betts (2010) stressed the importance of an integrated approach to tackle this subject and the need to consider cross-sectorial impacts and socio-economic aspects in future studies.

At regional level, the impacts of climate change on wheat crop yield and/or water use giving site-specific results have been extensively assessed (Saadi et al., 2015; Valverde et al., 2015; Jalota et al., 2014; Kersebaum and Nendel, 2014; Montesino-San Martín et al., 2014; Guo et al., 2010; Luo et al., 2005; Eitzinger et al., 2003). Further, a handful of studies have tackled the economic aspects of climate change at farm scale (e.g. Münch et al., 2014; Reidsma et al., 2010). None have, however, integrated the assessment of all three sustainability components into one framework to calculate the trade-offs between economic, environmental and social dimensions for the climate change impacts on winter wheat. The integration of LCA with crop growth models or LCA with outputs from general circulation models (GCMs), has recently become common practice to assess the impacts of different agricultural systems on the environment (e.g. Niero et al., 2015; Tendall and Gaillard, 2015; Röder et al., 2014; Mushtaq et al., 2013; Nemecek et al., 2011). Yet the combination of all these modelling tools used to assess the sustainability of wheat systems in a humid climate is a novel framework that deserves attention.

Therefore, the aim of this study is to assess the sustainability of winter wheat production at a farm level, adopting irrigation for adaptation to climate change in a typical temperate climate in the East of England region (UK). It will adopt an integrated modelling approach to estimate potential trade-offs between water savings, energy consumption (greenhouse gas [GHG] emissions) and economic benefits under current and future climate scenarios. This integrated approach makes a significant contribution to the carbon accounting of crop production in general and the impacts of intensification through irrigation in particular. Finally, the suggested framework could easily be replicated in different case studies and for other crops.

2. Material & methods

The study was divided into the following stages:

2.1. Selection of a 'typical' farm

Table 1
Wheat production summary statistics for England and the east of England for 2011. (*Source*: Defra, 2011b; Defra, 2011c).

Indicator	England	East of England	East of England/England (%)
Farmed area ($\times 10^6$ ha)*	8.89	1.38	15.5
Total number of farms*	53,090	8147	15.0
Wheat area ($\times 10^6$ ha)*	1.79	0.50	28.0
Wheat yield (t ha^{-1})	7.73	7.21	93.3
Average farm size (ha)*	153.3	195.4	127.5
Wheat production (Mt)	13.8	3.6	26.1
Wheat output (million £)	1984.64	573.51	28.9
Total crop output (million £)	7724.42	1979.58	25.6

* Data relates to 2010.

The case study farm was selected to reflect the average regional farm characteristics in the East of England (Table 1). Therefore, we assumed that the farm was 200 ha, practising rotational agriculture with winter wheat occupying 50 ha annually. The chosen on-farm irrigation system was a hose reel fitted with either a raingun or boom, the most common method of irrigation in the UK according to Defra (2011a), using an all year abstraction licence from a nearby river and a diesel pump. We modelled irrigation needs assuming a deep, uniform sandy–loam soil, with a depth of 4 m and total available water of 120 mm/m, as irrigation in England is more likely to be used on lighter, more drought-prone soils (Daccache et al., 2011). We additionally considered a deep uniform silty–clay–loam soil, with a depth of 4 m and a total available water of 210 mm/m, which is a heavier soil, because most wheat is currently grown on heavier soils (Bailey, 1990; El Chami et al., 2015).

2.2. Climate data and climate scenarios

The observed climate dataset used in this study was daily data (1970 to 1991) from a meteorological weather station located at Cambridge, Cambridgeshire (52.24°N, 0.10°W). Data included rainfall, reference evapotranspiration (ET_0) and maximum and minimum temperature for the historical baseline period (Fig. 1).

To generate the future weather dataset, a LARS-WG stochastic weather generator was used (Semenov and Barrow, 1997) to produce daily weather from GCM outputs at a single site. The LARS-WG utilises semi-empirical distributions for the lengths of wet and dry day series, daily precipitation and daily solar radiation (Racsko et al., 1991; Daccache et al., 2010).

The emission scenarios used are those developed by the IPCC (Nakićenović et al., 2000), and known as SRES (Special Report on Emission Scenarios) in which each scenario combines two sets of divergent tendencies. One set varies between strong economic values and strong environmental values, the other set varies between increasing globalisation and increasing regionalisation (IPCC, 1999). The scenarios are commonly known as A1 (economic–global), B1 (environmental–global), A2 (economic–regional) and B2 (environmental–regional). For this

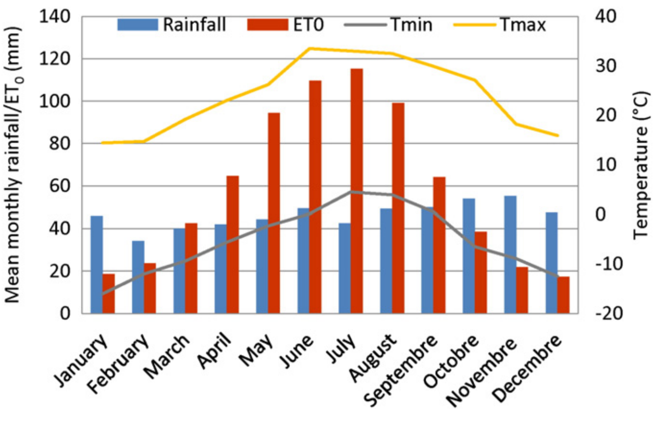

Fig. 1. Monthly observed climate dataset at Cambridge.