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# Large changes in Great Britain's vegetation and agricultural land-use predicted under unmitigated climate change

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## Abstract

The impact of climate change on vegetation including agricultural production has been the focus of many studies. Climate change is expected to have heterogeneous effects across locations globally, and the diversity of land uses characterising Great Britain (GB) presents a unique opportunity to test methods for assessing climate change effects and impacts. GB is a relatively cool and damp country, hence, the warmer and generally drier growing season conditions projected for the future are expected to increase arable production. Here we use state-of-the-art, kilometre-scale climate change scenarios to drive a land surface model (JULES; Joint UK Land Environment Simulator) and an ECONometric AGricultural land use model (ECO-AG). Under unmitigated climate change, by the end of the century, the growing season in GB is projected to get  $>5$  °C warmer and 140 mm drier on average. Rising levels of atmospheric CO<sub>2</sub> are predicted to counteract the generally negative impacts of climate change on vegetation productivity in JULES. Given sufficient precipitation, warming favours higher value arable production over grassland agriculture, causing a predicted westward expansion of arable farming in ECO-AG. However, drying in the East and Southeast, without any CO<sub>2</sub> fertilisation effect, is severe enough to cause a predicted reversion from arable to grassland farming. Irrigation, if implemented, could maintain this land in arable production. However, the predicted irrigation demand of  $\sim 200$  mm (per growing season) in many locations is comparable to annual predicted runoff, potentially demanding large-scale redistribution of water between seasons and/or across the country. The strength of the CO<sub>2</sub> fertilisation effect emerges as a crucial uncertainty in projecting the impact of climate change on GB vegetation, especially farming land-use decisions.

## Introduction

Agriculture accounts for 72% of land use in the United Kingdom and provides employment for close to half a million people (National Statistics 2019). The quality of farmland and the terrain determines how farmers use their land, either as arable for growing crops or grassland for farming livestock. Arable land accounts for approximately 30% of all agricultural land and contributes approximately 40% of the total farm

income (National Statistics 2019). Generally, arable farming is more profitable in Great Britain (GB) than livestock farming (noting that profits of virtually all agricultural activities fluctuate from year to year depending on input and output prices). However, factors including climate, poor soil and steep slopes mean that in current conditions arable farming is not economically viable in some regions of GB. Most of the arable cropland is situated in the lowlands of south east GB, which have relatively warm temperatures and

lower rainfall (figure 1). In contrast, in upland areas such as north, west and south west GB the arable share is lower due to factors such as the terrain, climate (cold temperatures and excessive rainfall), and poor soils. These regions are more suitable for livestock farming.

Climate change is predicted to generate a range of impacts on GB, including warmer temperatures, wetter winters and drier summers, as well as increased variability in extreme weather events (see Chan *et al* 2018, Gohar *et al* 2018). Higher concentration of atmospheric CO<sub>2</sub> increases the efficiency of photosynthesis, but the extent to which CO<sub>2</sub> fertilisation will increase agricultural yields is uncertain (Lobell and Asseng 2017). There are also uncertain climate change impacts on pests and disease incidence. The overall impact of future changes in temperature and precipitation on GB agriculture is expected to be positive (at least for moderate levels of change) but highly spatially heterogeneous. Previous studies (Fezzi *et al* 2014, Fezzi and Bateman 2015) project significantly positive impacts in the wettest and coldest regions of GB and a slightly negative effect in the south east, in line with the larger scale assessments (e.g. Olesen and Bindi 2002, Schlenker and Roberts 2009). Furthermore, adaptation measures can mitigate the negative impacts and boost the positive ones (Challinor *et al* 2014). A key adaptive measure is irrigation. Currently, in GB, irrigation plays a very small role in total agricultural water use as most land is rainfall fed, in 2017 less than 1% of the total water abstracted in England was used for agriculture (DEFRA 2019). However, irrigation is already used extensively for potato crops, and irrigation demand is predicted to increase sharply by the 2030s (Thomas *et al* 2010).

Recent studies (Kendon *et al* 2014, Chan *et al* 2018) have produced high resolution climate projections over the UK for 2100. These projections were produced with a Regional Climate Model (RCM) forced by RCP8.5 (Representative Concentration Pathway with radiative forcing reaching 8.5 W m<sup>-2</sup> in 2100) (Riahi *et al* 2007) on a 1.5 km × 1.5 km grid. The unprecedented high resolution nature of these projections allow for a highly spatially resolved look at land-use change, that is not possible with lower resolution models (Huntingford *et al* 2011, Wiltshire *et al* 2013). The high-resolution RCM also explicitly resolves convective storms and projects an increased likelihood of heavy summer precipitation and associated higher rates of runoff and drier soils (Kendon *et al* 2017). In the following, whilst we consider how these hydrological changes could influence the future need for irrigation, we are not yet able to model the effect of extreme events on land-use decisions.

Here we combine representations of land use decisions and ecosystem responses to climate change to evaluate potential future vegetation productivity, agricultural land-use, and irrigation demands in GB. We use the high-resolution RCM data for current and future climate periods (Kendon *et al* 2012, Kendon *et al* 2014, Chan *et al* 2018) to drive two state-of-the-art models—the

process-based JULES model and an empirically-derived spatially-explicit ECONometric AGricultural land use model; ECO-AG (Fezzi and Bateman 2011). The future projections from RCP8.5 show an extreme climate change scenario with >5 °C warming over GB by 2100. This contrasts with previous studies (Fezzi *et al* 2014, Fezzi *et al* 2015) on agricultural land use, which have considered moderate climate change and only up until the mid-century. JULES uses the fixed agricultural map produced by ECO-AG to prescribe regions of grassland and separates the effects of climate and CO<sub>2</sub> on vegetation. The latter allows us to evaluate the relative importance of the climate alone and the CO<sub>2</sub> fertilisation effect by analysing the changes in productivity of temperate grasses and broadleaf trees—proxies for grassland and forest productivity. ECO-AG does not include any CO<sub>2</sub> effects on vegetation because it is an empirical model built on historical data. However, in ECO-AG, we also consider a policy scenario of subsidising the full system costs of irrigation to farmers to support the possibility of arable farming.

## Methods

A summary of scenarios in this paper, and the model they correspond to, are listed in table 1.

### JULES model

JULES, is a state-of-the-art land surface model that forms the land surface component in the UK Met Office's Unified Model used for numerical weather prediction and climate modelling (Best *et al* 2011, Clark *et al* 2011). It calculates the fluxes of CO<sub>2</sub>, heat, water, and momentum between the land surface and atmosphere on a 30 minute timestep. The results generated for this paper were obtained using version 4.9 of the JULES model, using 9 different surface types, including five plant functional types (PFTs): broadleaf and needleleaf trees, temperate (C<sub>3</sub>) and tropical (C<sub>4</sub>) grasses, and shrubs, and four non-vegetation types: urban, lakes, bare soil and land-ice. Soil properties affecting hydraulics (e.g. water holding capacity and saturated soil hydraulic conductivity) and physical properties (e.g. heat capacity and albedo) are based on data from the high-resolution Harmonized World Soil Database (HWSD). Potential photosynthesis for C<sub>3</sub> and C<sub>4</sub> plants is based on Collatz *et al* (1991) and Collatz *et al* (1992), respectively, and is scaled by  $\beta$ , a water availability factor which is 1 when there is no stress, to calculate net assimilation (Clark *et al* 2011). Plant respiration ( $R_p$ ) is parameterised based on nitrogen concentration (here fixed and not limiting), canopy temperature, and soil moisture, and gross photosynthesis minus  $R_p$  gives the net primary productivity (NPP). Carbon (C) is allocated evenly between leaf and root biomass, with maximum and minimum leaf area index (LAI) prescribed per PFT. Once a plant reaches the maximum LAI, C is allocated to growth (increasing height and adding woody biomass). Previous

evaluation of the JULES carbon cycle has focused on global performance of the model (Harper *et al* 2016, Harper *et al* 2018). On a global scale, JULES represents NPP of temperate grasslands very well (NPP in both the model and observations is  $0.304 \text{ kg m}^{-2} \text{ year}^{-1}$ ), but overestimates the NPP of temperate mixed forests by about 30%. In this paper, we analyse the modelled NPP of temperate grasses as representative of GB grasslands and of broadleaf trees as representative of GB woodlands. Soil moisture is also updated each timestep based on incoming rainfall minus losses through evaporation, surface runoff, and sub-surface runoff (Best *et al* 2011). The latter includes drainage through the bottom of the soil column, while surface runoff occurs due to rain falling on saturated soils. The soils are represented with 4 layers extending to 3 m depth. We analyse the runoff for each grid cell to indicate the locations of water abundance that can be used for irrigation. The daily climate driving data and  $\text{CO}_2$  concentration used in the scenarios listed in table 1 are described below.

### ECO-AG model

The ECONometric AGricultural land use model, ECO-AG, is empirically-derived and spatially-explicit. It builds on the data and the econometric methodology developed by Fezzi and Bateman (2011), subsequently forming an essential component of the UK National Ecosystem Assessment (NEA 2011, Bateman *et al* 2013) and its follow-on project (Bateman *et al* 2014). This approach is also recently used by Fezzi *et al* (2014) and Fezzi *et al* (2015) who appraise the environmental impact of climate change adaptation on land use and water quality. We use a simpler and updated version of the model that focuses on the determinants of agricultural land use allocation between arable and grassland by predicting the production decisions at  $2 \text{ km} \times 2 \text{ km}$  grid resolution. Specifically, the simpler version of the model predicts the share of agricultural land devoted to arable farming without allocating that arable land to specific crop types. The ECO-AG model is an econometric model estimated on  $2 \text{ km} \times 2 \text{ km}$  grid June Agricultural Census data from 1972 to 2010 ([www.edina.ac.uk](http://www.edina.ac.uk)) and driven by observational climate data comprising 30 year averages of temperature and rainfall for the growing season (April–September) and a series of control variables including soil types, terrain, policy variables and prices, which are accounted for using yearly fixed effects. The model is estimated as quasi-maximum likelihood binomial logit (e.g. Papke and Wooldridge 1996). The resulting model predictions of agricultural land use agree well with observed data, for example Fezzi and Bateman 2011 and Fezzi *et al* 2014. While agricultural revenues change greatly with output prices, arable land is typically the highest-value agricultural activity in GB (exceptions are some intensive dairy farms mainly located in central and south west GB), and therefore provides a proxy for

**Table 1.** Table of scenarios (simulation number in the left column), and corresponding model used to analyse impacts on vegetation and agricultural land use under differing boundary conditions. ECO-AG does not have the facility to incorporate  $\text{CO}_2$  levels hence all scenarios with ECO-AG contain a (No) in the  $\text{CO}_2$  column. Irrigation can either be switched on (Yes) or turned off (No) in both models.

#	Model and Scenario name	Climate	$\text{CO}_2$	Irrigation
1	ECO-AG Baseline state	Present	No	No
2	JULES Baseline state	Present	Present	No
3	ECO-AG Climate only	Future	No	No
4	JULES Climate only	Future	Present	No
5	JULES Irrigation only	Present	Present	Yes
6	ECO-AG Climate & Irrigation	Future	No	Yes
7	JULES Climate & $\text{CO}_2$	Future	Future	No
8	JULES Climate, $\text{CO}_2$ & Irrigation	Future	Future	Yes

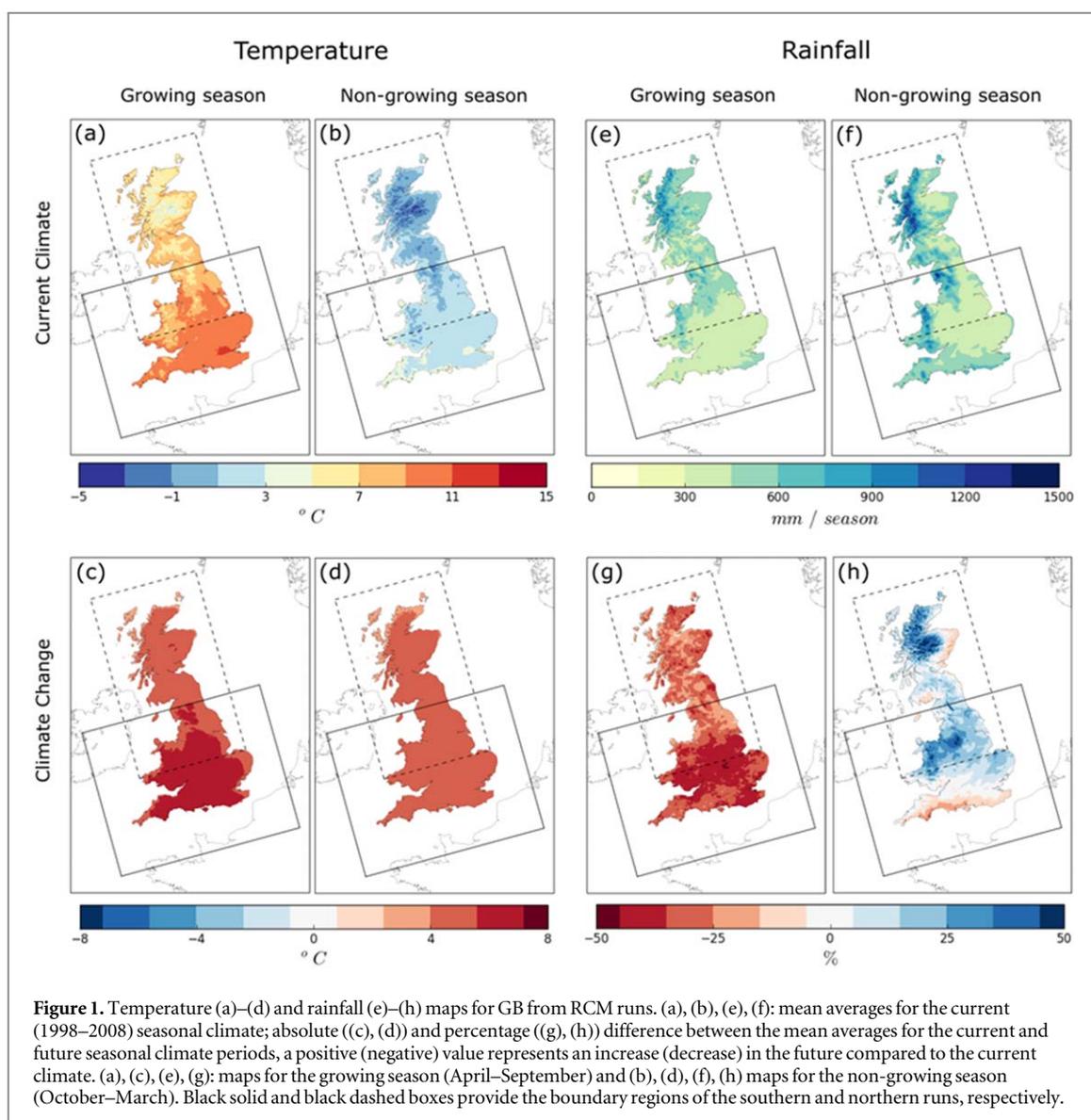
understanding the effects of climate change on the 72% of GB land area under agricultural production.

### Irrigation demand

Irrigation can be switched ‘on’ or ‘off’ in both the JULES and ECO-AG models. In JULES (simulations #5 and #8, table 1), irrigation removes all water stress. Specifically, irrigation is assumed to be unlimited, applied any day of the year and at any land grid cell to all plant functional types, such that the soil moisture stress factor  $\beta$  is always 1. Similarly in ECO-AG (simulation #6, table 1), irrigation is unlimited but instead can be viewed as ‘additional rainfall’. If the rainfall falls below an empirically derived optimal threshold required for crop growth (280 mm per season), ECO-AG allows for irrigation to be implemented by supplying sufficient water to farmers to reach that same level. Therefore, this has the same effect as rainfall matching the optimal level for crop growth. The optimal threshold was calculated using data from the US Great Plains and EurAsia—regions with comparable arable extent and climate to GB.

### Climate and $\text{CO}_2$ driving data

We use climatological data from RCM runs at  $1.5 \text{ km} \times 1.5 \text{ km}$  spatial resolution and daily temporal resolution. 11 year climate realisations for the whole of GB were constructed by combining simulations of the current climate (1998–2008) (Kendon *et al* 2012) and a future climate for the end of the century also over a 11 year period (Kendon *et al* 2014) for southern GB with the corresponding simulations for northern GB (Chan *et al* 2018). The simulations for the south and north were combined using a piecewise linear weighting function for locations where the datasets overlap. This was designed to create a smooth transition from one set to the other with more significance applied to data values which lie further in from the boundary



than those that are closer due to errors often picked up at the boundaries in the RCM runs. These south and north combined RCM runs for present and future time periods provide the climate driving data used for the JULES scenarios listed in table 1.

For the present-day climate data, the RCM used current  $\text{CO}_2$  concentrations, which had a maximum of 386.5 ppm (corresponding to roughly the levels seen in 2009), while for the future a prescribed concentration was set at 936 ppm. This future concentration corresponds to the  $\text{CO}_2$  concentration at 2100 in RCP8.5 (Riahi, *et al* 2007). This scenario assumes a continuously increasing global population that has slow economic growth with little progress made on efficient technologies. Consequently, due to high energy demands from an increasing population a move towards coal-intensive technologies with high greenhouse gas (GHG) emissions is made. The reason for studying the RCP8.5 scenario is twofold; first it highlights the impacts on vegetation and agricultural land use under unmitigated climate change, and

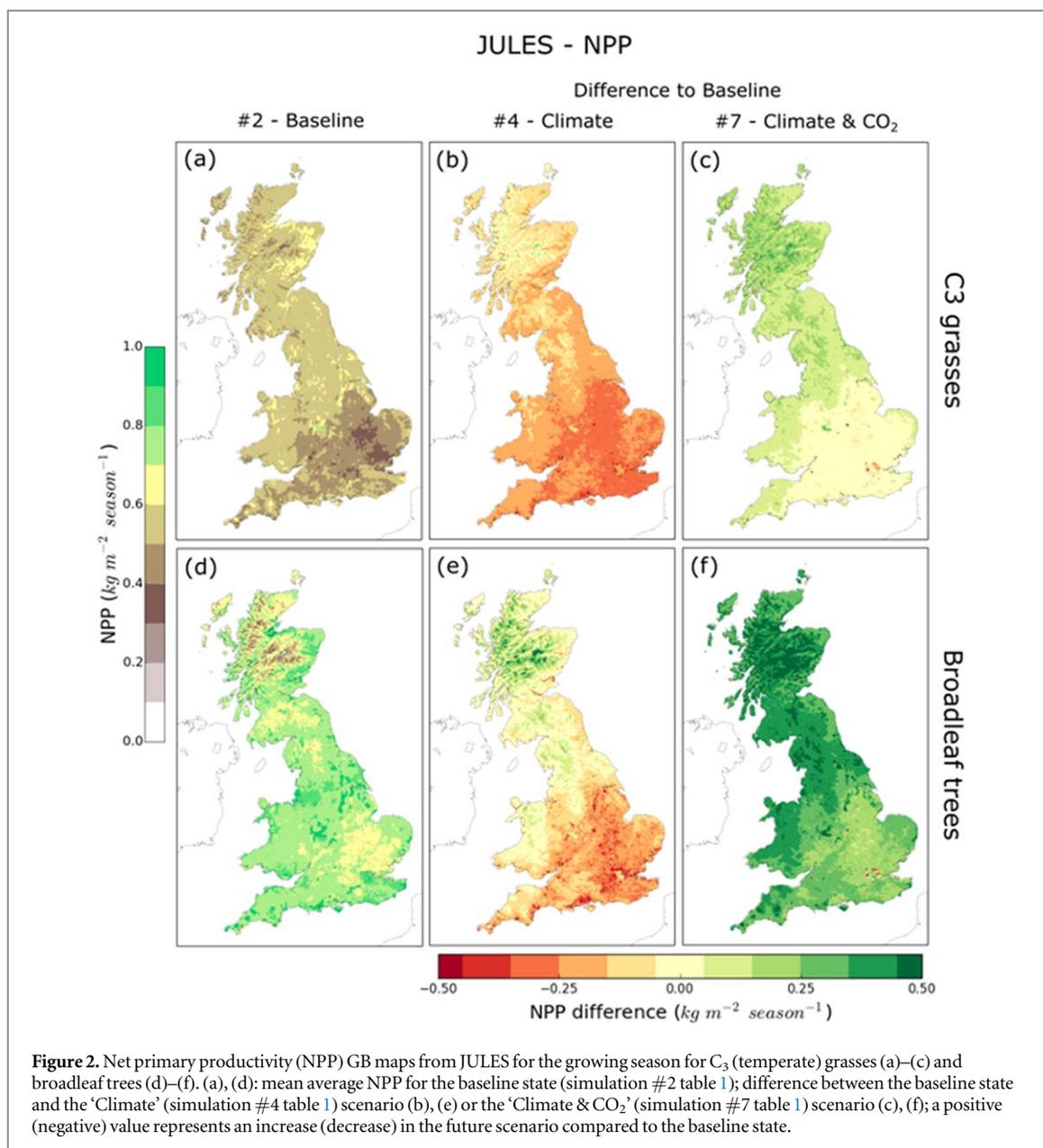
second it is the only scenario available at such unprecedented high resolution for GB in 2100.

The ECO-AG model baseline predictions (simulation #1, table 1) are calculated using observational climate data comprising 30 year averages of temperature and rainfall for the growing season (April–September) between 1960 and 1989. Such predictions agree well with observed data, for example Fezzi and Bateman (2011) and Fezzi *et al* (2014). The projected future climate data used in ECO-AG is bias corrected to account for any systematic bias in the modelled climate projections. The bias correction was performed by calculating the mean differences between the RCM present-day climate and the observed data for the period 1960–1989, and subtracting these amounts from the future RCM projection.

## Results

### Climate change

Figure 1 displays the RCM temperature (a)–(d) and rainfall (e)–(h), with the black solid and black dashed



boxes indicating the boundary regions of the south and north GB runs, respectively. The mean temperature profile for the current climate snapshot (1998–2008) for both the growing season (April–September; figure 1(a)) and the non-growing season (October–March; figure 1(b)), shows that northern GB is colder than the south and the southeast is the warmest in the growing season. There is a very significant increase in temperature in both seasons by the end of the century, which is more pronounced in the growing season—an average increase across GB of 5.4 °C in the growing season (figure 1(c)) compared to a rise of 4.7 °C out of the growing season (figure 1(d)).

The rainfall maps (figures 1(e), (f)) show that the western and northern areas of GB are considerably wetter than the east and south during the growing season. The difference maps show that the growing season (figure 1(g)) becomes drier by an average of 32% (140 mm per season), while the non-growing season

(figure 1(h)) is wetter by 7% (37 mm per season) on average across GB. Drying during the growing season is generally more pronounced in west, central and southern GB than it is in northern GB.

#### Changes to grass and tree productivity

In the baseline state (simulation #2 table 1), the mean simulated NPP across GB and across vegetation types is  $0.608 \text{ kg m}^{-2} \text{ year}^{-1}$  (interquartile range of  $0.554\text{--}0.681 \text{ kg m}^{-2} \text{ year}^{-1}$ ). For comparison, mean MODIS (Zhao and Running 2010, Running *et al* 2011; processed with AppEEARS 2019) NPP over GB was  $0.737 \text{ kg m}^{-2} \text{ year}^{-1}$  (from 2000–2008), with an interquartile range of  $0.641\text{--}0.816 \text{ kg m}^{-2} \text{ year}^{-1}$ . Thus, whilst the mean predicted NPP is slightly lower than the MODIS NPP, it overlaps the estimates derived from remote sensing.

The baseline NPP for temperate (C<sub>3</sub>) grasses in the growing season is shown in figure 2(a) (simulation #2

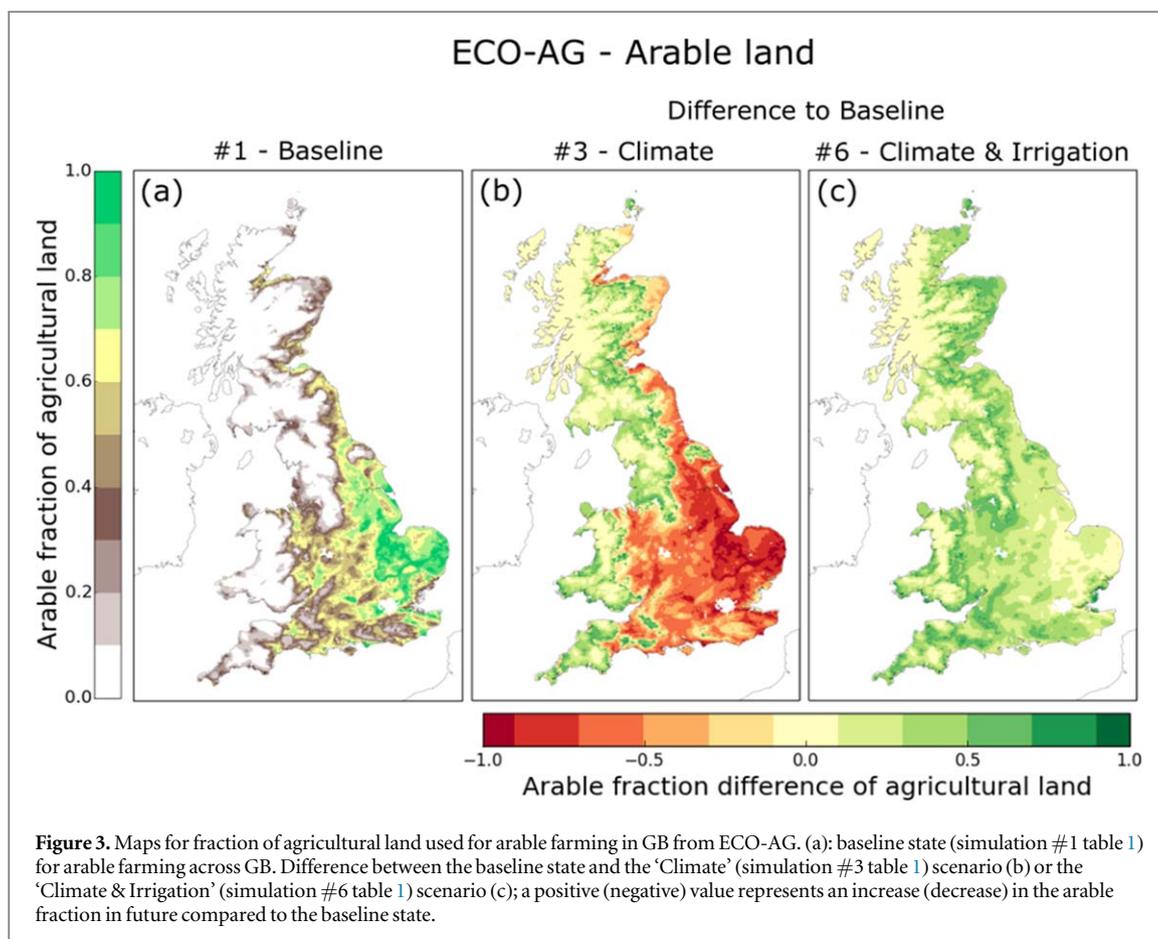


table 1). Grass NPP is currently highest in wet and mild temperature locations e.g. western, and central-northern GB, coinciding with areas of high rainfall, used mainly for farming livestock. In the south east, water limitation impacts grass production even under current climatic conditions. Under unmitigated climate change (figure 2(b), simulation #4 table 1), but without the enhanced productivity due to increased CO<sub>2</sub> (Wiltshire *et al* 2013), grass productivity is predicted to decline in most locations except mountainous parts of northern GB. The already water limited central and south east GB regions are affected the most. However, the physiological effect of future increases in CO<sub>2</sub> on C<sub>3</sub> plants (figure 2(c), simulation #7 table 1) leads to more efficient water use, counteracting the impacts of climate change almost everywhere and permitting increases in productivity in many locations that are relatively cool under the present climate.

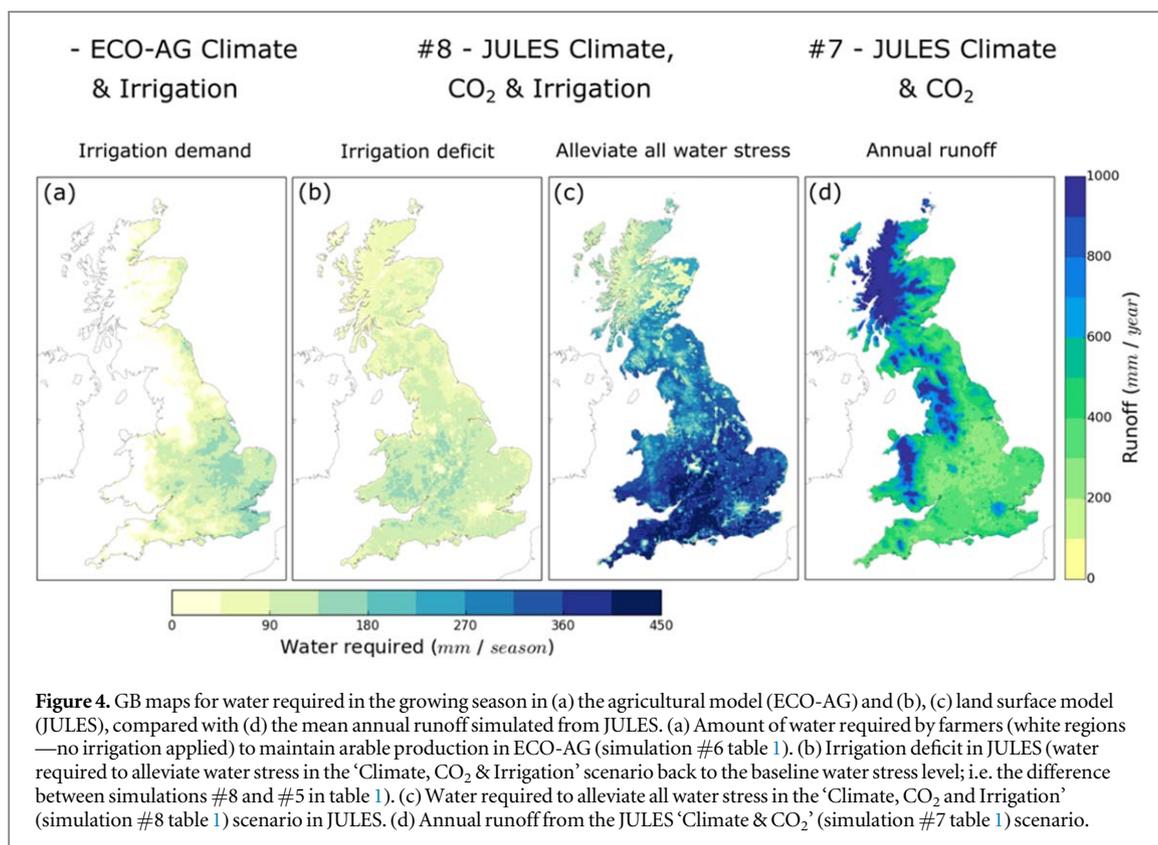
The NPP of broadleaf trees is fairly uniform in the baseline state (figure 2(d), simulation #2 table 1). The exceptions are the south east (water limited) and the mountainous regions in north GB (cooler temperatures), which have lower productivity rates. Setting aside any physiological effect of elevated CO<sub>2</sub> the impact of climate change is generally less severe for broadleaf trees than for temperate grasses (compare figures 2(e) and (b)), with a decline in tree NPP largely restricted to central and southern GB (figure 2(e),

simulation #4 table 1). In contrast, broadleaf trees in the highlands of northern GB benefit from the warmer conditions, creating a heterogeneous response across GB. Combined with the physiological effect of increased CO<sub>2</sub>, broadleaf tree productivity increases across GB, even in the water limited region of south east GB (figure 2(f), simulation #7 table 1).

#### Agricultural land use

Figure 3(a) shows the current fraction of agricultural land that ECO-AG predicts as arable (simulation #1 table 1). On average 33% of agricultural land across GB is currently allocated to growing crops, with south east GB having the highest fraction and with central and many parts of the east coast of GB having more than half of agricultural land under crops. In the wetter western and cooler northern regions of GB, agricultural land is predominantly used as grassland for farming livestock, because the climate makes arable farming of crops less viable.

Figure 3(b) shows the predicted change in the arable fraction of agricultural land under the future unmitigated climate change scenario (simulation #3 table 1). Throughout GB, the hotter and drier growing season results in an advancement of arable land to the west as indicated by the green colour. However, the currently arable dominated regions of central and south east GB experience major changes away from arable to grassland, because of water shortage; the



climate has become too dry to grow crops. This is consistent with other locations of similar arable extent and climate to GB, such as the US Great Plains and northern EurAsia (10W to 50E, 43N to 60N), where land cover data from the European Space Agency Climate Change Initiative (Kirches *et al* 2015) and mean growing season rainfall values from 1988–2017 (CRU TS4.02 (Harris *et al* 2014)) indicate a sharp decline in arable cover for rainfall below the optimal threshold used in ECO-AG. Overall, arable land drops from 33% to 22% of agricultural land across GB. Recall however that ECO-AG does not consider the physiological effects of increased CO<sub>2</sub> that are predicted for the C<sub>3</sub> grasses in JULES (figure 2(c), simulation #7 table 1), which could counteract the loss of arable production. However, ECO-AG can consider the impact of irrigation, which can have a substantial effect upon land use to which we now turn.

#### Irrigation demand

One policy scenario that could be implemented to maintain arable production in south east GB is to provide irrigation to farmers. One permutation of such a scenario would be that, once rainfall falls below some optimal threshold for crop growth, farmers are supplied with water up to that level. This scenario is shown for ECO-AG in figure 3(c). This scenario (simulation #6 table 1) still displays the advancement of arable to the west and north but now the large areas of arable land in south east GB are maintained, and even enhanced in some places, reflecting the positive

impacts of temperature increases once moisture requirements are met. Now the average share of GB agricultural land allocated to arable production increases to 61% (compared with 33% for the baseline state)

However, figure 4(a) shows the substantial irrigation demand entailed in this scenario (simulation #6 table 1), approaching 200 mm per growing season required in south east GB to maintain arable production rather than allow reversion to grassland and rough grazing. Similarly, in the land surface model JULES, figure 4(b) shows that the irrigation deficit (water required to alleviate the water stress back to baseline levels from climate change and the physiological impact of CO<sub>2</sub>; difference between simulations #8 and #5, table 1) is approximately 150 mm per growing season across GB (slightly reduced in north GB). To alleviate all water stress in JULES, such that there is no restriction on water in the land surface model, for the future scenario (simulation #8, table 1), requires more than 350 mm in southern GB but still close to 300 mm in central-northern GB (figure 4(c)). The annual average runoff, simulated from JULES (simulation #7, table 1), is shown in figure 4(d) for comparison as a measure of water availability (noting the difference in the scale). Figure 4(d) indicates an abundance of water available in the mountainous regions of west and north west GB, exceeding 1000 mm of runoff per year. In contrast, large regions of south east GB are water limited, only 200–400 mm of runoff per year.

## Discussion

Previous process-based model studies have predicted that future climate change alone (without a CO<sub>2</sub> fertilisation effect) will negatively impact the productivity of vegetation in GB (Huntingford *et al* 2011). This trend is reversed when combined with the physiological effect of increased CO<sub>2</sub> (Wiltshire *et al* 2013). Our results support these findings, showing that on average productivity is predicted to decline under unmitigated climate change alone, but to increase when the physiological effect of CO<sub>2</sub> is included. Unlike the aforementioned global studies, our unprecedented high-resolution GB simulations allow us to identify the south east as a location where the combination of unmitigated climate change and increased CO<sub>2</sub> leads to little overall predicted productivity change for grasslands.

Experimental studies support the theory that elevated CO<sub>2</sub> concentrations will raise photosynthesis rates while decreasing stomatal conductance (Nowak *et al* 2004). However, the degree to which the CO<sub>2</sub> fertilisation effect counteracts for the negative impacts of climate change on productivity is uncertain. Previous work evaluating the net primary productivity response of 7 different process-based vegetation models, under the same unmitigated emissions RCP8.5 scenario used in this paper, shows that JULES predicts the strongest CO<sub>2</sub> fertilisation effect amongst the models (Friend *et al* 2014). Therefore our 'Climate & CO<sub>2</sub>' (simulation #7 table 1) results with JULES probably give an over-optimistic view of future productivity changes and in reality the south east might experience a decline in grass productivity under unmitigated climate change and increased CO<sub>2</sub>.

Under the 2009 UK Climate Projections medium emissions scenario, arable farming in 2060 is predicted to advance to the west and north of GB with a small decline in intensity expected in the south east (Fezzi *et al* 2014, Fezzi *et al* 2015). Whilst our analysis also shows an increase of arable production to the west and north, the more extreme climate change scenario causes the previously arable dominant south east to be completely reversed to grassland livestock farming by the end of the century. This is due predominantly to a deleterious effect of climate drying on the productivity of arable farming. However, our predictions need to be treated with caution for three reasons. First, we use ECO-AG significantly outside the range of climate used for estimation of this empirically-based model—although the relationship used is supported by other studies of e.g. wheat production in temperate climates (Gourdji *et al* 2013, Asseng *et al* 2015). Second, ECO-AG does not consider the effect of CO<sub>2</sub> fertilisation increasing plant water use efficiency, which could counteract the projected decrease in arable production. Thirdly, land use will be strongly affected by

investments and input and output prices. The version of ECO-AG we are using in this paper assumes prices to be fixed to the level occurred in the last year of the data of estimation, i.e. 2010. Additionally, a meta-analysis of studies of crop yield under climate change generally show declines in wheat production in temperate regions under climate warming, but this can be counteracted by adaptation, as can the deleterious effects of drying (Challinor *et al* 2014). A more sophisticated econometric land-use model would also allow for the study of the impacts extreme events on productivity and subsequently farmer decisions. In particular, the RCM we use projects an increased likelihood of heavy summer precipitation in GB in 2100 (Kendon *et al* 2014, Chan *et al* 2018).

Two further omissions here are changes to the length of the growing season and nitrogen limitation. Under climate change the length of the growing season is expected to increase with both an earlier onset and later finish (Christiansen *et al* 2011). However, any change in growing season length will affect both arable and grassland farming and thus the division of land between these uses is expected to be minor. Although crop yield is likely to increase, the probability of drought conditions due to increased water use of plants under a lengthened growing season (Christiansen *et al* 2011) and decline in precipitation could limit this increase. Furthermore, under elevated CO<sub>2</sub> levels, previous studies (Conroy and Hocking 1993, Cotrufo *et al* 1998) have shown that nitrogen concentration is significantly reduced in plant tissue and therefore reduces the quality of the crop. In this study we have assumed that nitrogen is not limiting in either model. This assumes there is sufficient fertiliser application to aid crop production. More generally, nitrogen can limit vegetation response to elevated CO<sub>2</sub> (Thornton *et al* 2007). However, in GB there is widespread volatile N deposition on ecosystems not subject to fertiliser application. This has already been observed to boost productivity even in the most N-limited upland ecosystems (Kirkham 2001). Hence N limitation of the carbon cycle response is less of an issue in GB than many other ecosystems.

Our study suggests that irrigation as an adaptation measure has considerable potential to boost net primary production of GB vegetation and prevent the predicted shift away from arable farming in south east GB under unmitigated climate change. However, the corresponding predicted water (irrigation) demand of the order of 200 mm per growing season is large when compared to the predicted annual runoff (a proxy for water availability), which ranges between 200 and 400 mm over large areas of south east GB. Note, that the JULES results in particular, may provide a small overestimation for irrigation demand. In the JULES model runs irrigation is applied to all plant functional types but trees are typically not irrigated in GB.

Furthermore, groundwater could supply some of the water for agricultural irrigation in certain regions and is already used in some of the most intensive and productive arable areas of south east GB, however, there are limitations and potential environmental consequences from the overuse of groundwater. This suggests not only that a substantial redistribution of water between seasons would be required—implying technical measures such as increased reservoir storage for example—but also a large-scale redistribution of water geographically across the country, from the high-rainfall, mountainous regions of western and northern GB. We leave whether such water redistribution is feasible, physically or economically, as a topic for future research.

## Conclusion

Our study uses two alternative modelling approaches—the process-based JULES model and the empirically-based ECO-AG model. Results are broadly consistent between these two approaches and together they highlight both similarities and some important differences from previous work.

Our unprecedented high-resolution, multi-model study predicts that unmitigated climate change alone would cause major changes in GB vegetation and agricultural land-use by the end of this century. The combination of climate change and increased CO<sub>2</sub> is predicted to have a neutral effect on grassland productivity in central, south east GB whilst it increases elsewhere, along with broadleaf woodland productivity increasing everywhere. However, the JULES model probably overestimates the beneficial effects of CO<sub>2</sub> fertilisation on plant productivity, meaning declines in vegetation net primary production, particularly in the southeast, may be expected.

Projected >5 °C warming and ~140 mm drying per growing season in 2100, without a CO<sub>2</sub> fertilisation effect, is predicted to cause farmers to abandon arable farming in south east GB, whilst there is some westwards expansion of arable farming, leading to a net decline from 33% to 22% of GB agricultural land use. The lack of a CO<sub>2</sub> fertilisation effect in the ECO-AG model means declines in arable production are probably over-estimated.

Irrigation, if unrestricted, could maintain the south east of GB in arable production in the face of climate drying. However, the estimated demand for irrigation of up to 200 mm per growing season in some regions, is comparable to the annual water availability in those regions, implying not only a redistribution of water between seasons, but a large-scale geographical redistribution of water across Great Britain may be required to maintain arable farming.

Overall, the strength of the CO<sub>2</sub> fertilisation effect emerges as a crucial uncertainty in projecting the

impact of climate change on GB vegetation and farming land-use decisions, which need to be better constrained.

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## Data availability

The parameter values used for JULES is available from the suite u-ao645 and branch 'full\_UK' on the Rosie repository: <https://code.metoffice.gov.uk/trac/roses-u> (registration required). The modelled output data that support the findings of this study are openly available at Ritchie and Smith (2019). The JULES climate driving data is available for academic use only on the Met Office MASS data archive (registration required).

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