CORE Metadata, citation and similar papers at core.ac.uk

Provided by Open Research Exeter

Environmental Research Letters

ACCEPTED MANUSCRIPT • OPEN ACCESS

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

To cite this article before publication: Paul Ritchie *et al* 2019 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ab492b

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is **© 2019 The Author(s). Published by IOP Publishing Ltd**.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 3.0 licence, this Accepted Manuscript is available for reuse under a CC BY 3.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence https://creativecommons.org/licences/by/3.0

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the article online for updates and enhancements.

This content was downloaded from IP address 144.173.177.80 on 01/10/2019 at 12:05

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

Ritchie, Paul D.L.[1, 2]; Harper, Anna B.[1, 3]; Smith, Greg S.[1, 4]; Kahana, Ron[5]; Kendon, Elizabeth J.[5]; Lewis, Huw[5]; Fezzi, Carlo[4, 6]; Halleck-Vega, Solmaria[7]; Boulton, Chris A.[1, 2]; Bateman, Ian J.[1, 4]; Lenton, Timothy M.[1, 2]

[1]Global Systems Institute, University of Exeter, Exeter, EX4 4QE, United Kingdom

[2]College of Life and Environmental Sciences, Laver Building, University of Exeter, Exeter, EX4 4QE, United Kingdom

[3]College of Engineering, Mathematics and Physical Sciences, Laver Building, University of Exeter, Exeter, EX4 4QE, United Kingdom

[4]Land, Environment, Economics and Policy Institute, University of Exeter Business School, Xfi Building, Rennes Drive, Exeter, EX4 4PU, United Kingdom

[5]Met Office, Exeter, EX1 3PB, United Kingdom

[6]Department of Economics and Management, University of Trento, via Vigilio Inama 5, 38122 Trento, Italy.

[7]Wageningen University and Research, Leeuwenborch Building, Hollandseweg 1, 6706KN, Wageningen, The Netherlands

Keywords: *GB, unmitigated climate change, vegetation productivity, arable production, RCP 8.5*

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_2 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_2 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 ~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_2 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 Gohar, et al., 2018; Chan, et al., 2018). Higher concentration of atmospheric CO_2 increases the efficiency of photosynthesis, but the extent to which CO_2 fertilisation will increase agricultural yields is uncertain (Lobell & 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 & 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 & Bindi, 2002; Schlenker & 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^2 in 2100) (Riahi, et al., 2007) on a 1.5km x 1.5km 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 & 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_2 on vegetation. The latter allows us to evaluate the relative importance of the climate alone and the CO_2 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_2 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.

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 CO_2 levels hence all scenarios with ECO-AG contain a (No) in the CO_2 column. Irrigation can either be switched on (Yes) or turned off (No) in both models.

#	Model & Scenario name	Climate	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 & CO_2	Future	Future	No
8	JULES Climate, CO_2 & Irrigation	Future	Future	Yes

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_2, 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 (C3) and tropical (C4) 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 C3 and C4 plants is based on Collatz, et al., 1991 and Collatz, et al., 1992, respectively, and is scaled by β, 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 kg m^{-2} $year^{-1}$), 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 3m 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 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 & Bateman, 2011, subsequently forming an essential component of the UK National Ecosystem Assessment (Bateman, et al., 2013; NEA, 2011) 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 2km x 2km 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 2km x 2km grid June Agricultural Census data from 1972 to 2010 (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 & Wooldridge, 1996). The resulting model predictions of agricultural land use agree well with observed data, for example Fezzi & 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 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 β 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 CO_2 driving data

We use climatological data from RCM runs at 1.5km x 1.5km 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 CO_2 concentrations, which had a maximum of 386.5ppm (corresponding to roughly the levels seen in 2009), while for the future a prescribed concentration was set at 936ppm. This future concentration corresponds to the 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 & 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^{o}C in the growing season (Figure 1(c)) compared to a rise of 4.7^{o}C out of the growing season (Figure 1(d)).

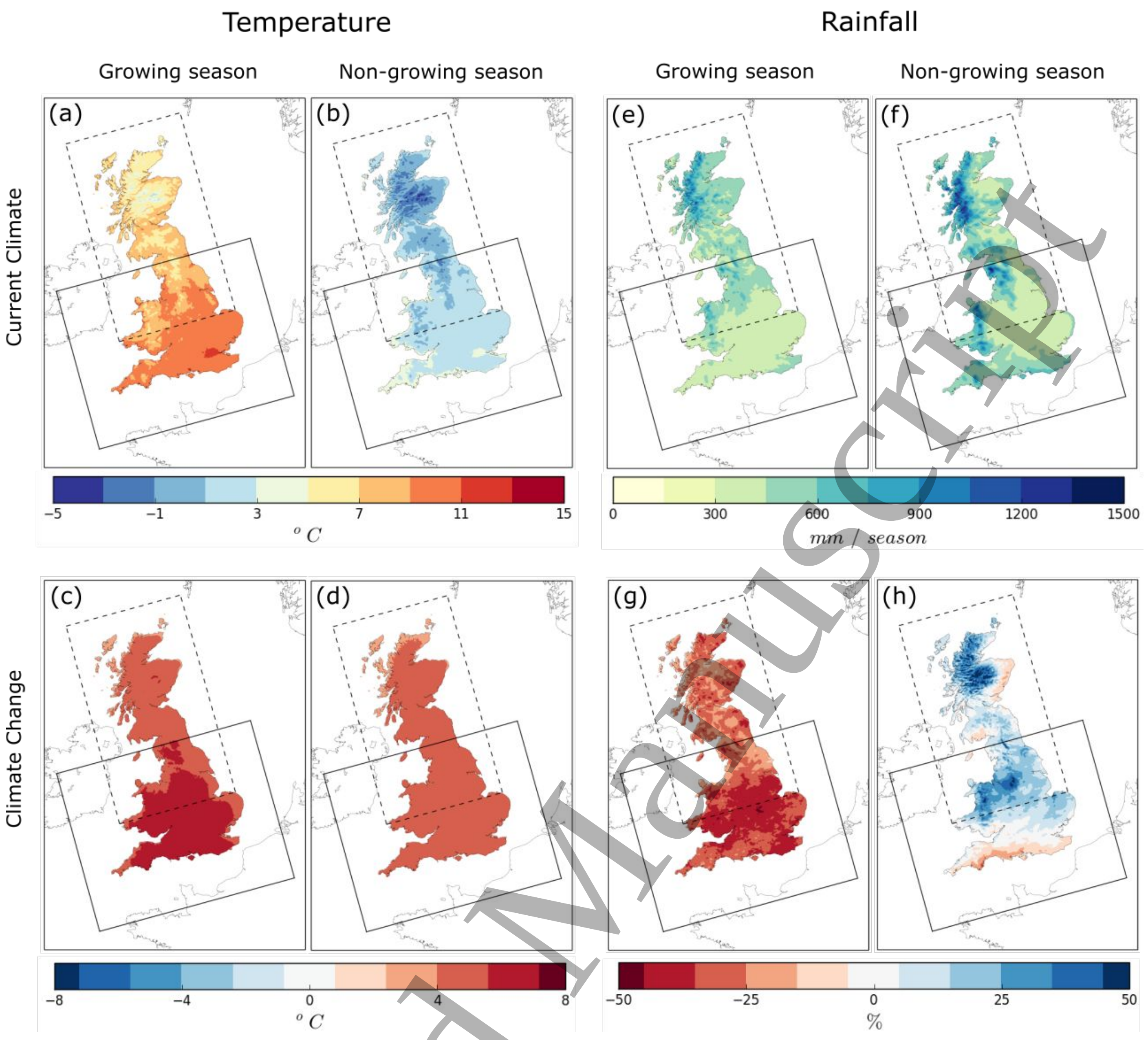

Figure 1: Temperature (a)-(d) and rainfall (e)-(h) maps for GB from RCM runs. (a), (b), (e), (f): mean averages for the current (1998-2008) seasonal climate; absolute ((c), (d)) and percentage ((g), (h)) difference between the mean averages for the current and future seasonal climate periods, a positive (negative) value represents an increase (decrease) in the future compared to the current climate. (a), (c), (e), (g): maps for the growing season (April-September) and (b), (d), (f), (h) maps for the non-growing season (October-March). Black solid and black dashed boxes provide the boundary regions of the southern and northern runs respectively.

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 kg m^{-2} $year^{-1}$ (interquartile range of 0.554-0.681 kg m^{-2} $year^{-1}$). For comparison, mean MODIS (Running, et al., 2011; Zhao & Running, 2010; processed with AppEEARS Team, 2019) NPP over GB was 0.737 kg m^{-2} $year^{-1}$ (from 2000-2008), with an interquartile range of 0.641-0.816 kg m^{-2} $year^{-1}$. 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 (C3) 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_2 (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_2 on C3 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.

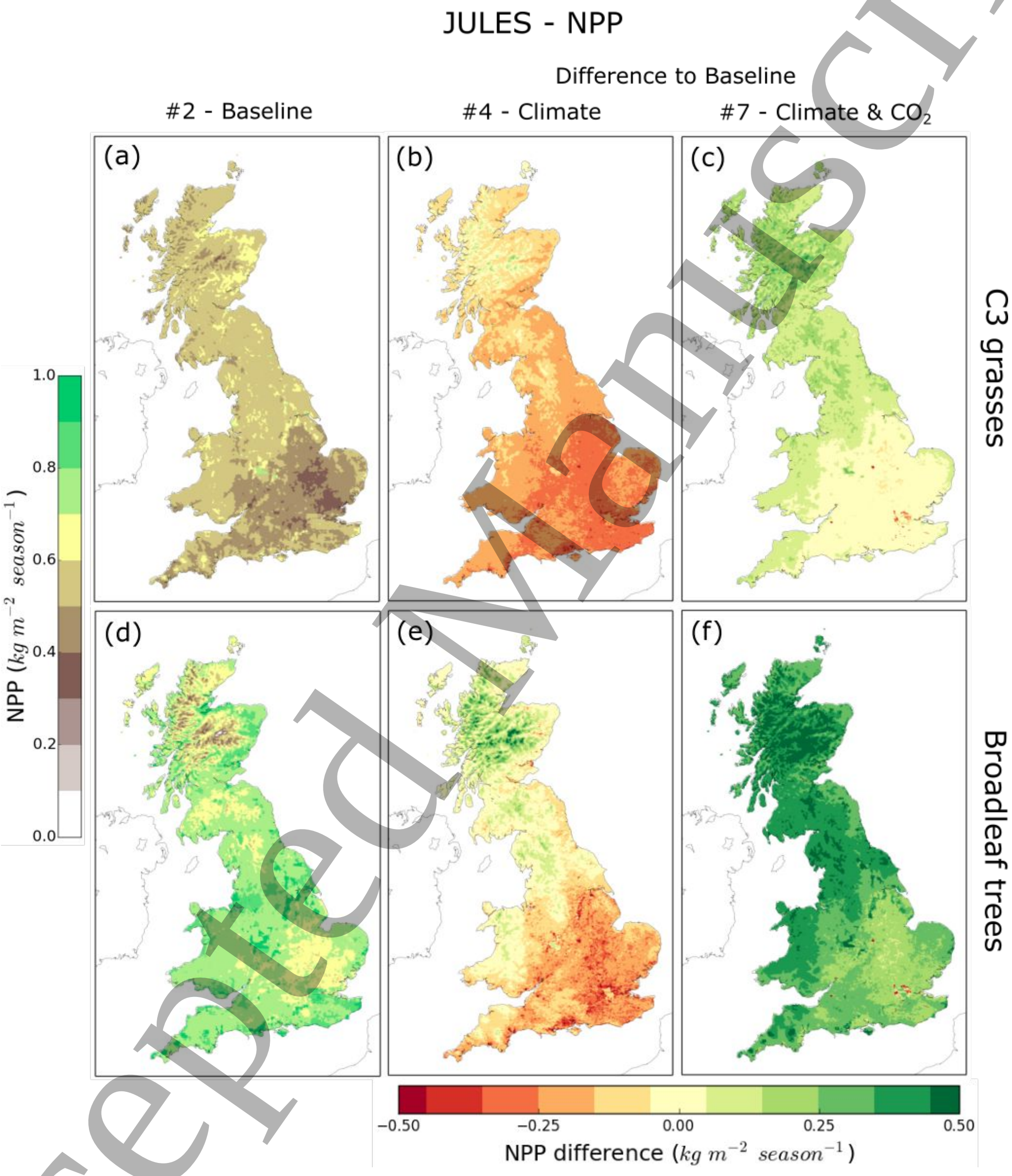

Figure 2: Net Primary Productivity (NPP) GB maps from JULES for the growing season for C3 (temperate) grasses (a)-(c) and broadleaf trees (d)-(f). (a), (d): mean average NPP for the baseline state (simulation #2 Table 1); difference between the baseline state and the 'Climate' (simulation #4 Table 1) scenario (b), (e) or the 'Climate & CO_2' (simulation #7 Table 1) scenario (c), (f); a positive (negative) value represents an increase (decrease) in the future scenario compared to the baseline state.

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_2 the impact of climate change is generally less severe for broadleaf trees than for temperate grasses (compare

Figures 2(e) and 2(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_2, 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_2 that are predicted for the C3 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.

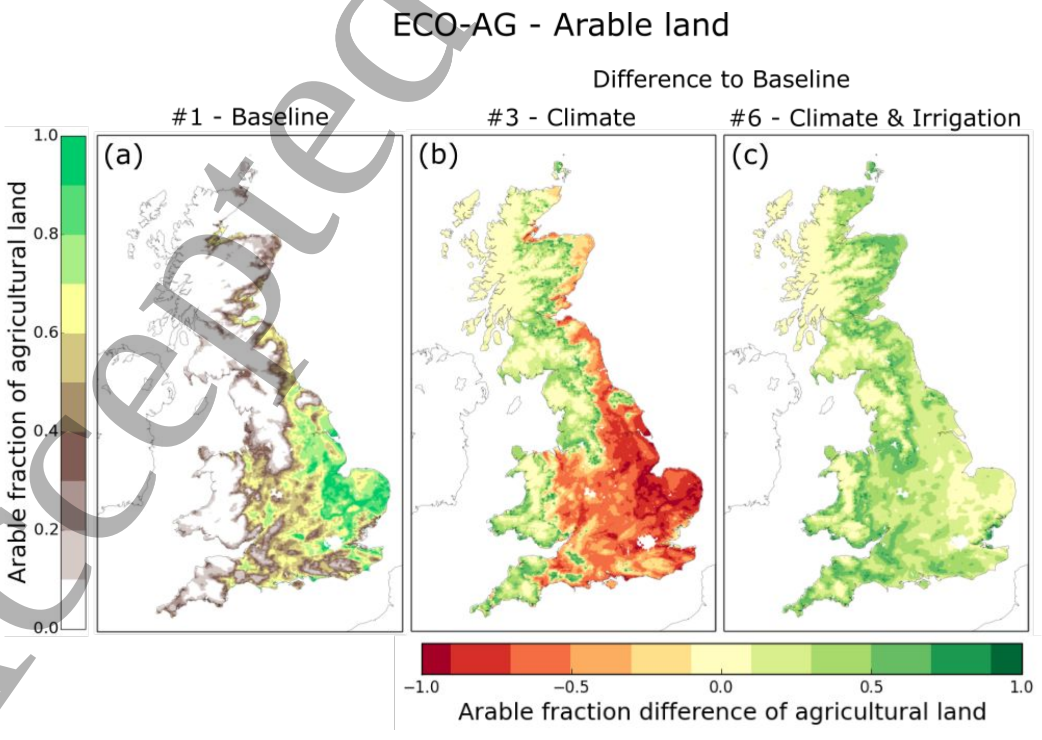

Figure 3: Maps for fraction of agricultural land used for arable farming in GB from ECO-AG. (a): baseline state (simulation #1 Table 1) for arable farming across GB. Difference between the baseline state and the 'Climate' (simulation #3 Table 1) scenario (b) or the 'Climate & Irrigation' (simulation #6 Table 1) scenario (c); a positive (negative) value represents an increase (decrease) in the arable fraction in future compared to the baseline state.

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_2; 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 1,000 mm of runoff per year. In contrast, large regions of south east GB are water limited, only 200-400 mm of runoff per year.

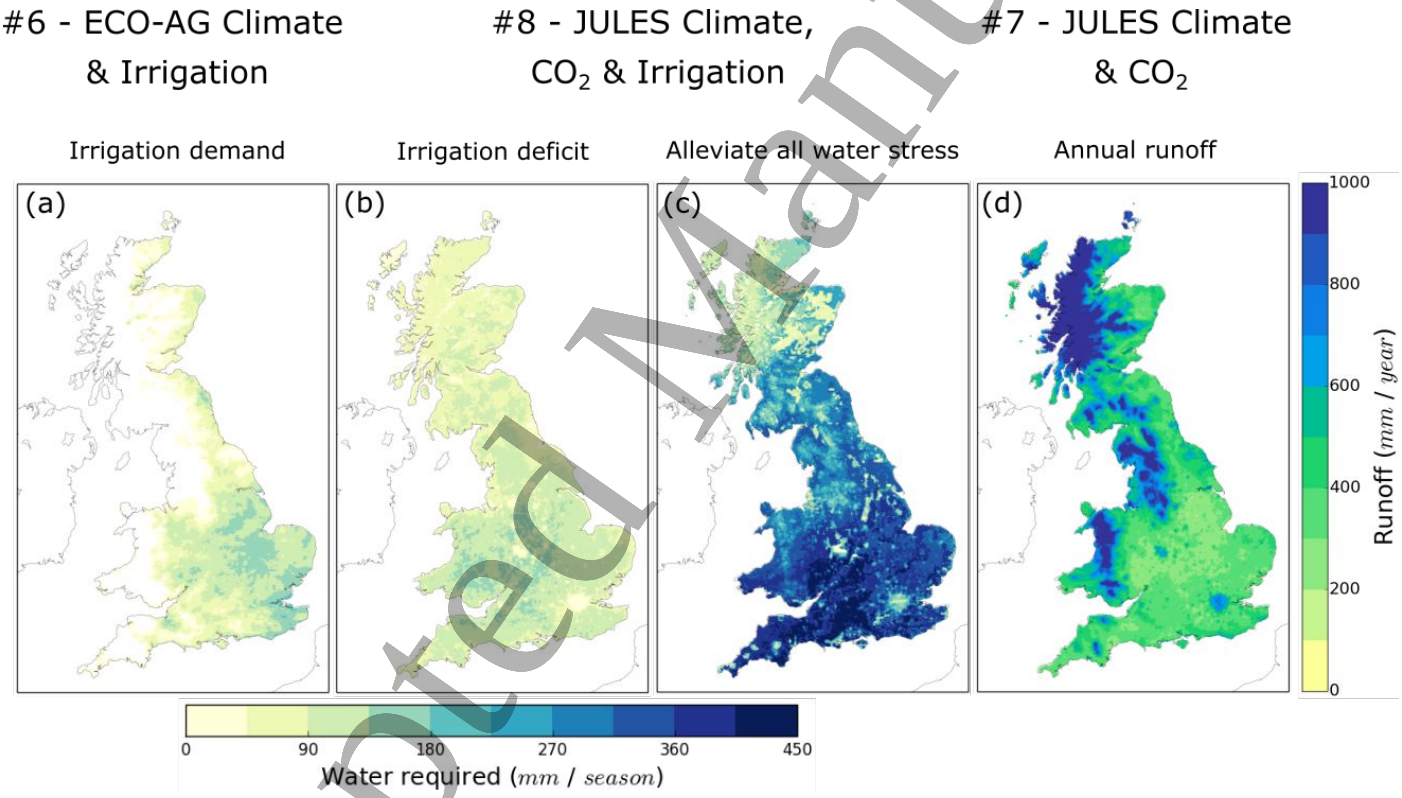

Figure 4: GB maps for water required in the growing season in (a) the agricultural model (ECO-AG) and (b, c) land surface model (JULES), compared with (d) the mean annual runoff simulated from JULES. (a): Amount of water required by farmers (white regions – no irrigation applied) to maintain arable production in ECO-AG (simulation #6 Table 1). (b) Irrigation deficit in JULES (water required to alleviate water stress in the 'Climate, CO_2 & Irrigation' scenario back to the baseline water stress level; i.e. the difference between simulations #8 and #5 in Table 1). (c) Water required to alleviate all water stress in the 'Climate, CO_2 & Irrigation' (simulation #8 Table 1) scenario in JULES. (d): Annual runoff from the JULES 'Climate & CO_2' (simulation #7 Table 1) scenario.

Discussion

Previous process-based model studies have predicted that future climate change alone (without a CO_2 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_2 (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_2 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_2 leads to little overall predicted productivity change for grasslands.

Experimental studies support the theory that elevated CO_2 concentrations will raise photosynthesis rates while decreasing stomatal conductance (Nowak, et al., 2004). However, the degree to which the CO_2 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_2 fertilisation effect amongst the models (Friend, et al., 2014). Therefore our 'Climate & CO_2' (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_2.

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_2 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_2 levels, previous studies (Conroy & 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_2 (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 200-400 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_2 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 over-estimates the beneficial effects of CO_2 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_2 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_2 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_2 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.

Acknowledgements

This work was supported by the NERC Valuing Nature Programme (NE/P007880/1). We thank Pete Falloon and Kate Halladay for discussions on the JULES output results. We acknowledge use of the Monsoon2 system, a collaborative facility supplied under the Joint Weather and Climate Research Programme, a strategic partnership between the Met Office and the Natural Environment Research Council. E.J. Kendon gratefully acknowledges funding from the Joint UK BEIS/Defra Met Office Hadley Centre Climate Programme (GA01101).

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 data that support the findings of this study are openly available at DOI.

References

AppEEARS, 2019. *Application for Extracting and Exploring Analysis Ready Samples (AppEEARS). Ver. 2.27. NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, USA..* [Online]
Available at: https://lpdaacsvc.cr.usgs.gov/appeears
[Accessed 6 August 2019].

Asseng, S. et al., 2015. Rising temperatures reduce global wheat production. *Nature climate change,* p. 143.

Bateman, I. et al., 2014. *UK National Ecosystem Assessment Follow-on. Work Package Report 3: Economic value of ecosystem services,* s.l.: UNEP-WCMC LWEC, UK.

Bateman, I. J. et al., 2013. Bringing ecosystem services into economic decision-making: land use in the United Kingdom. *Science,* pp. 45-50.

Best, M. et al., 2011. The Joint UK Land Environment Simulator (JULES), model description–Part 1: energy and water fluxes. *Geoscientific Model Development,* pp. 677-699.

Challinor, A. J. et al., 2014. A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change,* p. 287.

Chan, S. C., Kahana, R., Kendon, E. J. & Fowler, H. J., 2018. Projected changes in extreme precipitation over Scotland and Northern England using a high-resolution regional climate model. *Climate Dynamics,* pp. 1-19.

Christiansen, D. E., Markstrom, S. L. & Hay, L. E., 2011. Impacts of climate change on the growing season in the United States. *Earth Interactions,* 15(33), pp. 1-17.

Clark, D. et al., 2011. The Joint UK Land Environment Simulator (JULES), model description–Part 2: carbon fluxes and vegetation dynamics. *Geoscientific Model Development,* pp. 701-722.

Collatz, G. J., Ball, J. T., Grivet, C. & Berry, J. A., 1991. Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer. *Agricultural and Forest meteorology,* pp. 107-136.

Collatz, G. J., Ribas-Carbo, M. & Berry, J., 1992. Coupled photosynthesis-stomatal conductance model for leaves of C4 plants. *Functional Plant Biology,* pp. 519-538.

Conroy, J. & Hocking, P., 1993. Nitrogen nutrition of C3 plants at elevated atmospheric CO2 concentrations. *Physiologia Plantarum,* 89(3), pp. 570-576.

Cotrufo, M. F., Ineson, P. & Scott, A., 1998. Elevated CO2 reduces the nitrogen concentration of plant tissues. *Global Change Biology,* 4(1), pp. 43-54.

DEFRA, 2019. Water abstraction statistics: England, 2000 to 2017. *GOV.UK.*

Fezzi, C. & Bateman, I., 2015. The impact of climate change on agriculture: Nonlinear effects and aggregation bias in Ricardian models of farmland values. *Journal of the Association of Environmental and Resource Economists,* pp. 57-92.

Fezzi, C. et al., 2014. Valuing provisioning ecosystem services in agriculture: the impact of climate change on food production in the United Kingdom. *Environmental and Resource Economics,* Volume 57, pp. 197-214.

Fezzi, C. & Bateman, I. J., 2011. Structural agricultural land use modeling for spatial agro-environmental policy analysis. *American Journal of Agricultural Economics,* pp. 1168-1188.

Fezzi, C., Harwood, A. R., Lovett, A. A. & Bateman, I. J., 2015. The environmental impact of climate change adaptation on land use and water quality. *Nature Climate Change,* Volume 5, p. 255.

Friend, A. D. et al., 2014. Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO2. *Proceedings of the National Academy of Sciences,* pp. 3280-3285.

Gohar, G., Bernie, D., Good, P. & Lowe, J., 2018. UKCP18 Derived Projections of Future Climate over the UK. *Met Office.*

Gourdji, S. M., Sibley, A. M. & Lobell, D. B., 2013. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. *Environmental Research Letters,* p. 024041.

Harper, A. B. et al., 2016. Improved representation of plant functional types and physiology in the Joint UK Land Environment Simulator (JULES v4. 2) using plant trait information. *Geoscientific Model Development,* 9(7), pp. 2415-2440.

Harper, A. B. et al., 2018. Vegetation distribution and terrestrial carbon cycle in a carbon cycle configuration of JULES4.6 with new plant functional types. *Geoscientific Model Development,* 11(7), pp. 2857--2873.

Harris, I., Jones, P. D., Osborn, T. J. & Lister, D. H., 2014. Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset. *International journal of climatology,* 34(3), pp. 623-642.

Huntingford, C. et al., 2011. Highly contrasting effects of different climate forcing agents on terrestrial ecosystem services. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* pp. 2026-2037.

Kendon, E. J. et al., 2017. Do convection-permitting regional climate models improve projections of future precipitation change?. *Bulletin of the American Meteorological Society,* pp. 79-93.

Kendon, E. J. et al., 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change,* p. 570.

Kendon, E. J., Roberts, N. M., Senior, C. A. & Roberts, M. J., 2012. Realism of rainfall in a very high-resolution regional climate model. *Journal of Climate,* pp. 5791-5806.

Kirches, G. et al., 2015. *Land Cover CCI, Product User Guide, Version 2.0,* s.l.: ESA Climate Change Initiative - Land Cover project 2014.

Kirkham, F., 2001. Nitrogen uptake and nutrient limitation in six hill moorland species in relation to atmospheric nitrogen deposition in England and Wales. *Journal of Ecology,* 89(6), pp. 1041-1053.

Lobell, D. B. & Asseng, S., 2017. Comparing estimates of climate change impacts from process-based and statistical crop models. *Environmental Research Letters,* p. 015001.

National Statistics, 2., 2019. *AGRICULTURE IN THE UNITED KINGDOM 2018.* s.l.:GOV.UK.

NEA, U., 2011. The UK national ecosystem assessment technical report. *UNEP-WCMC, Cambridge.*

Nowak, R. S., Ellsworth, D. S. & Smith, S. D., 2004. Functional responses of plants to elevated atmospheric CO2–do photosynthetic and productivity data from FACE experiments support early predictions?. *New phytologist,* pp. 253-280.

Olesen, J. E. & Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. *European journal of agronomy,* Volume 16, pp. 239-262.

Papke, L. E. & Wooldridge, J. M., 1996. Econometric methods for fractional response variables with an application to 401 (k) plan participation rates. *Journal of applied econometrics,* Volume 11, pp. 619-632.

Riahi, K., Grübler, A. & Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change,* 74(7), pp. 887-935.

Running, S., Mu, Q. & Zhao, M., 2011. *MOD17A3 MODIS/Terra Net Primary Production Yearly L4 Global 1km SIN Grid V055 [Data set],* s.l.: NASA EOSDIS Land Processes DAAC.

Schlenker, W. & Roberts, M. J., 2009. Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of sciences,* Volume 106, pp. 15594-15598.

Thomas, B., Collier, R. & Green, L., 2010. *Climate Change Impacts and Adaptation - a Risk Based Approach,* s.l.: Defra research project final report for AC0310.

Thornton, P. E., Lamarque, J., Rosenbloom, N. A. & Mahowald, N. M., 2007. Influence of carbon-nitrogen cycle coupling on land model response to CO2 fertilization and climate variability. *Global biogeochemical cycles,* 21(4).

Wiltshire, A., Kay, G., Gornall, J. & Betts, R., 2013. The impact of climate, CO2 and population on regional food and water resources in the 2050s. *Sustainability,* pp. 2129-2151.

Zhao, M. & Running, S. W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science,* 329(5994), pp. 940-943.