Science of the Total Environment 900 (2023) 166390

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Bioenergy crop production and carbon sequestration potential under changing climate and land use: A case study in the upper River Taw catchment in southwest England

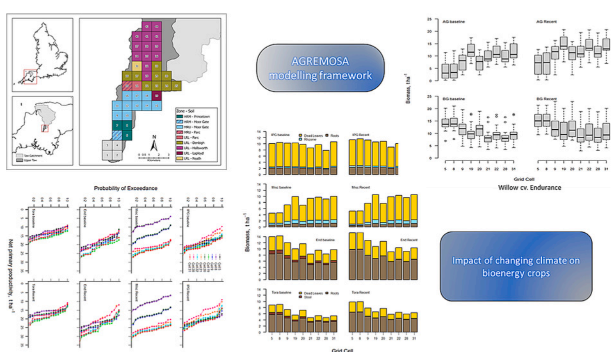
Prakash N. Dixit[a,*], Goetz M. Richter[a], Kevin Coleman[a], Adrian L. Collins[b]

[a] *Net Zero and Resilient Farming, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*
[b] *Net Zero and Resilient Farming, Rothamsted Research, North Wyke, Okehampton, Devon EX20 2SB, UK*

HIGHLIGHTS

- The effect of climate on biomass production and C sequestration was evaluated.
- Changing climate helps net primary productivity of perennial bioenergy crops.
- *Endurance* willow is the best of all crops for C sequestration in this environment.
- *Miscanthus* provides greater aboveground biomass than willow for bioenergy.
- Land use change from grassland to *Endurance* willow can enhance C sequestration potential.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Net zero
Miscanthus
Willow
Climate change
Carbon
Land conversion

ABSTRACT

Reductions in CO_2 emissions are essential to support the UK in achieving its net zero policy objective by around mid-century. Both changing climate and land use change (LUC) offer an opportunity to deploy suitable bioenergy crops strategically to enhance energy production and C sequestration to help deliver net zero through capturing atmospheric CO_2. Against this background, we applied process-based models to evaluate the extent of net primary productivity (NPP) losses/gains associated with perennial bioenergy crops and to assess their C sequestration potential under changing climate in the upper River Taw observatory catchment in southwest England. In so doing, we also determined whether LUC from permanent grassland to perennial bioenergy crops, considered in this study, can increase the production and C sequestration potential in the study area. The results show that a warming climate positively impacts the production of all crops considered (permanent grassland, *Miscanthus* and two cultivars of short rotation coppice (SRC) willow). Overall, *Miscanthus* provides higher aboveground biomass for energy compared to willow and grassland whereas the broadleaf willow cultivar '*Endurance*' is best suited, among all crops considered, for C sequestration in this environment, and more so in the changing climate. In warmer lowlands, LUC from permanent grassland to *Miscanthus* and in cooler uplands from permanent grassland to '*Endurance*', enhances NPP. Colder areas are predicted to benefit more from changing climate in terms of above and belowground biomass for both *Miscanthus* and willow. The study shows that the above LUC can help

* Corresponding author.
E-mail address: prakash.dixit@rothamsted.ac.uk (P.N. Dixit).

https://doi.org/10.1016/j.scitotenv.2023.166390
Received 29 April 2023; Received in revised form 15 August 2023; Accepted 16 August 2023
Available online 17 August 2023

augment non-fossil energy production and increase C sequestration potential if C losses from land conversion do not exceed the benefits from LUC. In the wake of a changing climate, aboveground biomass for bioenergy and belowground biomass to enhance carbon sequestration can be managed by the careful selection of bioenergy crops and targeted deployment within certain climatic zones.

1. Introduction

The demand for biomass for energy production is likely to increase in countries that have signed the Paris agreement (2015) and, more recently, the 26th United Nations climate change agreement directed through the Conference of the Parties (COP 26, 2021). These countries are committed to sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide (CO_2) emissions by 45 % by 2030, relative to the 2010 levels, to reach net zero by around mid-century (Glasgow Climate Pact, 2021).

Perennial bioenergy (PBE) crops can be a potential source of renewable energy (Murphy et al., 2013) and sink for soil C storage (Jorgensen, 2011) and could therefore be an attractive alternative to fossil fuels. Here, for example planting *Miscanthus* in the UK could offset 2–13 Mt. oil eq. yr^{-1}, contributing up to 10 % of current energy use, with 20–30 times lower total C cost of energy production (1.12 g CO_2-C eq. MJ^{-1}) than fossil fuels (McCalmont et al., 2017). The UK has been growing cellulosic crops for bioenergy since the early 2000s. In 2020, 121,000 ha of agricultural land was used for bioenergy crops in the UK and 7.2 million tonnes oil equivalent of plant biomass were used to produce electricity and heat (Gov.uk, 2021). Although there are no refineries in the UK that specifically process cellulosic crops for bioenergy, there are a number of power plants and anaerobic digestion plants that use cellulosic crops as a feedstock (DECC, 2012; REA, 2021). In 2017, renewable energy other than wind, solar and hydro-power, accounted for 9.4 % of the total energy produced in the UK and there is scope for more bioenergy from the expansion of biomass cropping (BEIS, 2018).

Grasslands represent over two thirds of the utilised agricultural area in the UK, of which 50 % is improved permanent grassland (Defra, 2016) which could produce biomass for bioenergy (Qi et al., 2018) and also sequester C (O'Mara, 2012). However, a substantial increase in PBE crop planting will be required to reach future targets for reductions in greenhouse gas emissions without impacting on high quality land (Lovett et al., 2014). This will have the potential to supply >60 % of the UK's total heat and electricity demand (Wang et al., 2014). Perennial bioenergy crops could also serve a secondary purpose, in contributing to negative emissions by C capture and storage (García-Freites et al., 2021). However, the important question here is whether the change from grassland to another, PBE crop, would sequester more atmospheric CO_2 (Agostini et al., 2015).

In England, *Miscanthus* and SRC willow are likely to dominate as PBE crops (Gallardo and Bond, 2011; Glithero et al., 2013). The high yield and low input demands make the fast-growing *Miscanthus giganteus* the PBE crop of choice for biomass (Heaton et al., 2010; Lewandowski et al., 2003; McCalmont et al., 2017). Nakajima et al. (2018) have highlighted the potential of *Miscanthus giganteus* for C sequestration especially, in relatively cooler regions similar to the one used in our study. The SRC willow is, however, an ideal species for SRC in the UK because of its vigorous shoot regeneration after coppicing, and its suitability for local regional climate and soil conditions (Britt et al., 1995). As a result, SRC willow has been identified as the PBE crop with the greatest potential for C mitigation across the UK (Smith et al., 2000a, 2000b). The roots of perennial crops persist longer than annual crops, which is important because soil organic C (SOC) is primarily derived from roots (Blanco-Canqui, 2016; Rasse et al., 2005). Thus, SRC willow has the potential for C sequestration over the typical lifetime (*i.e.,* 15 to 30 years) of a stand (Defra, 2001, 2002).

Climate change is likely to have variable effects across different locations with a diversity of land use in the UK, and, in turn, this presents a unique opportunity to assess the mitigation effects of LUC (Ritchie et al., 2019). Here, interactions of changing climate and LUC continue to need investigation in relation to large scale land conversion to PBE crops (Gallardo and Bond, 2011; Harayama et al., 2020). One reason is that substantial uncertainty surrounds the cropping transitions from grassland to PBE crops, since the former is a very large C sink itself. (Scurlock and Hall, 1998; Dass et al., 2018).

Process-based modelling of the development and growth of PBE crops like *Miscanthus* (Hastings et al., 2014; McCalmont et al., 2017) and SRC willow (Cerasuolo et al., 2016) provides the opportunity to explore how management, species choice and changing climate affect production, C partitioning, the environment and the subsequent supply chain (Hastings et al., 2014). Previous modelling studies characterized aboveground yields and soil C sequestration in SRC plantations (Grogan and Matthews, 2002; Isebrands et al., 1996). The question remains, however, as to how these two dedicated perennials would compare with permanent grassland in terms of biomass production, and C partitioning and sequestration in different topographic zones. This is especially, because the existing literature provides conflicting results regarding the organic C stored in the soil when land use is changed from grassland to *Miscanthus* or willow.

Given the above context and to ascertain the extent of impact of changing climate on the production and C sequestration potential of PBE crops, and how land use change might help exploit the benefits, if any, such a study is highly valuable. In this new study, we use process-based models to explore the productivity and C sequestration potential of different land use systems, across a pedo-climatically variable case study catchment, in a changing climate with the observed climate records. These land uses were: i) improved permanent grassland (IPG), and ii) the two perennial bioenergy crops *viz.* a) *Miscanthus* (*Miscanthus* × *giganteus*) and b) two cultivars of willow (*Salix spp.*). The objectives of this study were to: i) evaluate the extent of net primary productivity loss/benefits for PBE crops due to changing climate in a wet and warmer environment of southwest England; ii) assess the C sequestration potential of land use change from grassland to other PBE crops, and; iii) aid the selection of a PBE crop best suited for future climate in this environment for enhanced bioenergy production and carbon sequestration.

2. Materials and methods

2.1. Study site, climate and land use zones

The study site comprised a 44 km^2 area in the upper River Taw catchment (midpoint coordinates 50.725° N, 3.921° W) in Devon, southwest England. The study area is approximately 15 km in length stretching from the source of the river to just south of the town of North Tawton. Following the study reported by Hassall et al. (2022), we partitioned the study catchment into 44 grid cells each of 1 km × 1 km (Fig. 1). From the headwaters south of the Dartmoor granite plateau, the elevation drops from ~550 to 145 m above sea level.

The study area is characterized by three weather zones and seven soil types (Fig. 1). The zone of higher elevation and precipitation (comprising 8 grid cells, 1–8) was labelled as high rainfall moorland (HRM) (mean annual precipitation of 2178 mm, 1981–2019). This zone has cooler temperatures with an annual mean of 6.26 °C (1981–2019). The zone of medium elevation and precipitation (comprising 11 cells, 9–18, 20) was labelled as the medium rainfall upland (MRU) (mean annual precipitation of 1628 mm). This zone has an annual mean temperature of 6.88 °C. Finally, the zone with lowest elevation and precipitation (comprising 25 cells, 19, 21–44) was labelled as low rainfall lowland (LRL). This zone was generally warmer, with an annual mean temperature of 8.05 °C and the lowest mean annual precipitation amounting to 1191 mm.

2.2. Data required for model simulations

2.2.1. Climate data

The observed climate data to run the scenarios were derived from the meteorological station located at the North Wyke Farm Platform. Daily maximum and minimum temperatures, precipitation, global solar radiation, relative humidity and wind speed and direction spanning 1981 to 2019 were converted into hourly timeseries, applying sinusoidal functions to temperature, daylength and global radiation (Goudriaan and van Laar, 1994). The general validity of local evidence for precipitation duration of 6 h was assumed for precipitation data disaggregation. The atmospheric CO_2 concentration levels for different time periods were determined from the study of Meinshausen et al. (2011) (Meinshausen, M., personal communication, November 29, 2014, data available at http://www.pik-potsdam.de/~mmalte/rcps/). The climate data were divided into two scenario periods to simulate the changing trend of climate. The weather for 1981–2000 was considered to represent the "baseline climate" whereas 2001–2019 was taken as a period of "recent climate" in the study area.

The consistent changes in both mean annual temperatures and precipitation (Table S1) evident in the two climate scenarios for the three weather zones (*viz.* HRM, MRU and LRL) evidence climate change at micro catchment level. Here, the trends of changing climate are also consistent in that as the mean temperatures always go up, the precipitation goes down for all three weather zones in the study area. More specifically, the HRM zone experienced the greatest change in mean annual precipitation but the smallest change in mean annual temperature. The LRL, however, experienced the smallest change in precipitation but the greatest change in mean temperature. The corresponding changes in precipitation and mean temperature in the MRU zone were in between those for the HRM and LRL zones. Whilst the changes in absolute numbers are different, the percentage changes remained more or less the same at ~7 % for precipitation and 5.4 % for mean temperature. The changes in atmospheric CO_2 concentrations were considered similar for all three weather zones and were ~ 10 % higher in the recent climate scenario (390 ppm, corresponding to year 2010) compared with the baseline climate (355 pm, corresponding to year 1990).

Whilst long-term means of annual precipitation and temperature evidence a general trend for climate in the study area, the corresponding monthly patterns provide more insight into the associated impact of changing climate on the growth and production of a crop. Whilst the annual precipitation decreased under recent climate, it did not decrease in the summer months from June to August (Fig. 2). Hence it appears that the increase in summer precipitation might have a positive impact on crop growth and production.

The mean air temperature increased in every month and the trends were consistent with the highest increase in the warmer LRL zone and the lowest increase in the cooler HRM zone. The highest increase in mean air temperature was in April followed by October and June (all >0.5 °C). In all other months, the temperature increase was <0.5 °C, except in November, but only for the LRL zone, where the increase was 0.52 °C (Table S1, Fig. 2).

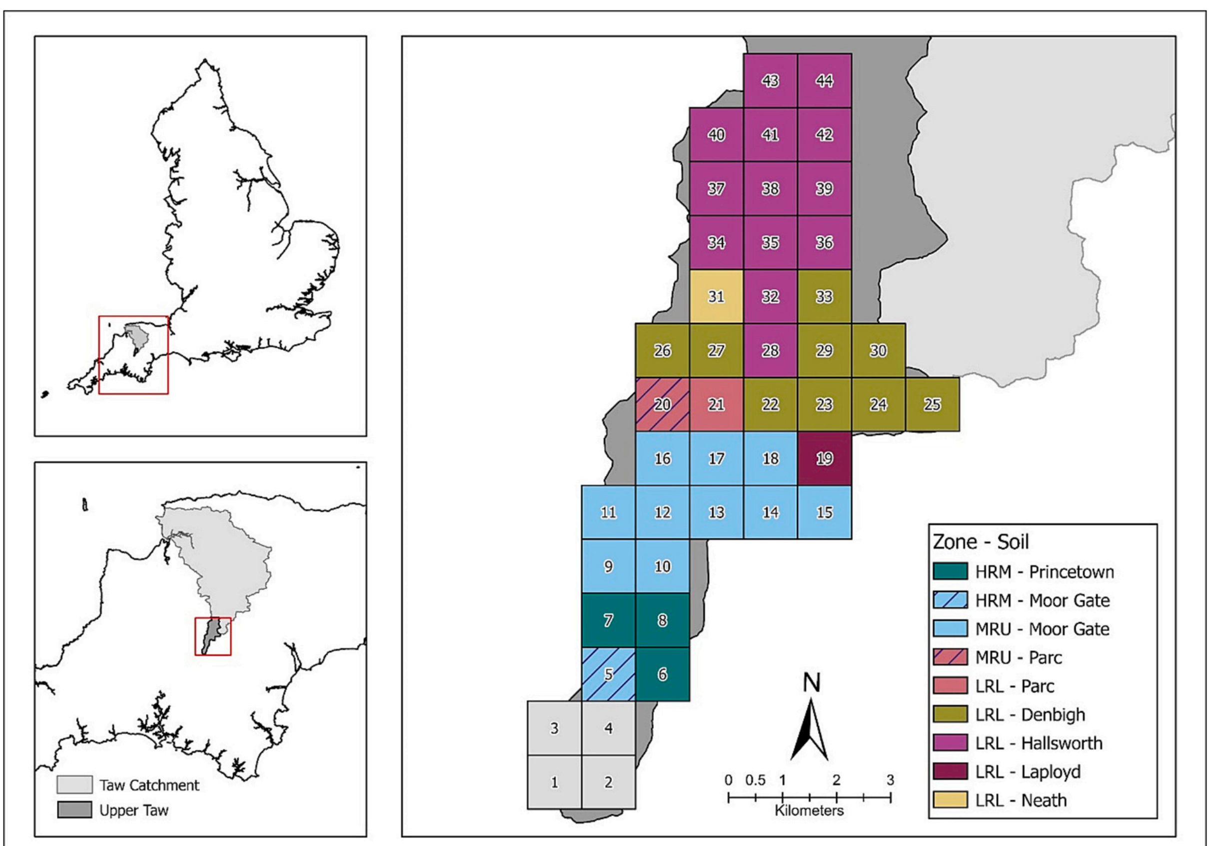


Fig. 1. The location of the 44 km^2 study site in the upper River Taw catchment in southwest England. Different zones of weather and soil classification are shown and each cell covers an area of 1 km × 1 km. The different weather zones are high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL). The soil classification was determined using the NATMAP Vector data product from the National Soil Resources Institute© Cranfield University (NSRI) (CEH, 2017).

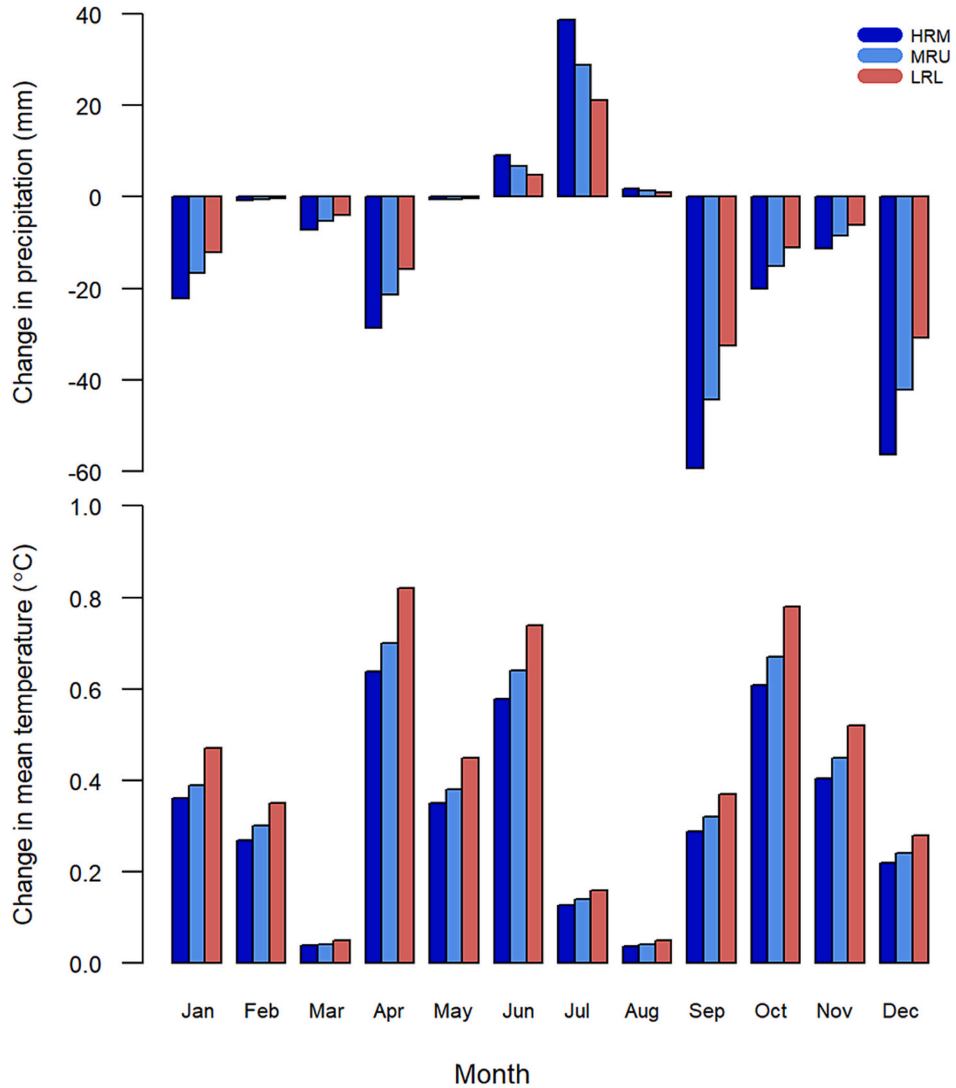


Fig. 2. Changes in monthly precipitation and mean temperature from baseline (1981–2000) to recent climate (2001–2019) in the high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL) zones.

2.2.2. *Soils data*

Soil information was determined for the dominant soil series for each cell using the NATMAP Vector data product from the National Soil Resources Institute© Cranfield University (NSRI) (CEH, 2017). The van Genuchten (van Genuchten, 1980) parameters were estimated from texture, organic matter and bulk density using pedotransfer functions (Wosten et al., 1999). The soils varied from sandy to clayey, with the plant available water capacity ranging from 164 mm up to 150 cm depth to 207 mm up to 120 cm depth. Most soils had higher (ranging from 5 to 15 %) organic C contents in the surface 15 to 25 cm layer (Table S2). Four grid cells (1–4) in the HRM zone were bog and not suitable for cultivation and were therefore removed from the model simulations, leaving only 4 cells in that zone and an overall total of 40 grid cells.

2.3. *Simulation scenarios*

2.3.1. *Land use simulations*

LINGRA and LUCASS, as implemented in AGREMOSA (AGRicultural Environment MOdelling and Systems Analysis), were used to simulate the two land uses: i) improved permanent grassland (IPG), and ii) the two perennial bioenergy crops *viz.* a) *Miscanthus* (*Miscanthus* × *giganteus*) and b) two cultivars of willow (*Salix spp.*). The two cultivars of willow were *'Endurance'* (*S. rehderiana* × *S. dasyclados*), a broad-leaf (leaf width 20–27 mm) closed-canopy cultivar and '*Tora*' (*S. schwerinii* × (*S. viminalis* × *viminalis*)), a narrow-leaf (leaf width 14–19 mm), open-canopy cultivar. We used the ISBA hydrological model in this study and evapotranspiration was calculated as a part of the energy balance using the Penman-Monteith approach (Allen et al., 1998). Although AGREMOSA simulates water-limited production and does not take nutrients into account, the model was, however, parameterized to simulate IPG based on 150 kg N ha^{-1} application as outlined by Qi et al. (2018). Both *Miscanthus* and willow simulations were performed assuming non-N-limited growth; in practice only 50 kg N ha $^{-1}$ are applied after each harvest (Gregory et al., 2018) which provides high yield.

2.3.2. *Crop management*

Improved permanent grasslands (IPG) were simulated as a mixture of sown and indigenous grasses and legumes of intermediate productivity receiving an annual N application of 150 kg N ha^{-1}. The grass cutting regime was kept at twice a year on June 21 and October 30, following the study of Qi et al. (2017) and the best practice guide (AHDB, 2014). *Miscanthus* was harvested every year on 1st March (Julian day 60), whilst the SRC-willows were coppiced in a 3-year cycle, which was previously found to give the highest biomass yields for willows (Stolarski et al., 2019), and were cut on 14th February (Julian day 45).

2.3.3. Simulated grid cells and current land use

Seven soil types combined with three weather zones defined nine distinct combinations for the model simulations. These were: (i) grid cell 5 Moorgate in the HRM zone; (ii) grid cells 6–8 Prince town in the HRM zone; (iii) grid cells 9–18 Moorgate in the MRU zone; (iv) grid cell 19 Laployd in the LRL zone; (v) grid cell 20 Parc in the MRU zone; (vi) grid cell 21 Parc in the LRL zone; (vii) grid cells 22–27, 29–30, 33 Denbigh in the LRL zone; (viii) grid cells 28, 32, 34–44 Hallsworth in the LRL zone, and; (ix) grid cell 31 Neath in the LRL zone (Fig. 1, Table S2). Improved permanent grassland (IPG) is the dominant land use in the lowlands and rough grazing in the uplands. Anticipating obvious increases in production under any land use other than very low productivity rough grazing, and to make our analysis simple and applicable to wider areas with similar soil and temperature regimes across the region where IPG is the current land use, IPG was considered as the baseline land use in the study area. All the land uses were simulated in each of the above grid cell. Detailed soil information is given in Table S2. The first two years (1981 and 1982) and the last year (2019) of the simulation results were removed from analysis. The first two years were removed to stabilize the simulation, the so-called 'warm up' period. Because the crop sown in 2019 required the following year of weather data as well, the outputs were not complete and hence, were removed. Thus, we had 36 years of simulations (*i.e.*, 18 years for each climate scenario) for analysis.

2.4. Model description

We used AGREMOSA, a modelling and optimization framework of process-based models simulating water-limited production of perennial crops, which include grassland and biomass crops. It simulates the water and energy balance at an hourly, and plant phenology and growth, at a daily time-step. AGREMOSA implements the sink-source interaction approach of LINGRA (Hoglind et al., 2001; Schapendonk et al., 1998) to simulate the growth of grasslands (Qi et al., 2017) and perennial biomass crops like tall grasses *e.g.*, *Miscanthus* (Triana et al., 2011; Ni et al., 2019) and SRC-willow (Cerasuolo et al., 2016). Fig. S1 shows the functional structure diagram of the AGREMOSA modelling framework.

LINGRA (LINTUL-GRASS) is a sink-source interaction model developed for the growth of small forage grasses (Schapendonk et al., 1998; Hoglind et al., 2001). It was extended by generalising the phenology and C allocation modules to account for the effects of late harvest and senescence in extensive and semi-natural grasslands. These modifications affect pheno-morphological development (sink formation) and light interception, photosynthesis and carbohydrate allocation (source formation) (Qi et al., 2017). Potential growth rates of the component plant organs (leaf, stem, root) which determine the respective allocation demands are defined as the sink. The aboveground sink strength is the sum of the potential growth of leaves and stems which set the respective carbohydrate allocation rates and are a function of tiller density, elongation rates and respective morphological parameters. Elongation rates are affected by water stress described by a logistic function (Sinclair, 1986; Richter et al., 2006) and are a linear function of average daily temperature (Hazard et al., 2006; Hoglind et al., 2001). The ability of LINGRA to simulate the roots, rhizome, dead leaves and litter along with the aboveground biomass makes it suitable to simulate the biomass for bioenergy and belowground biomass input for C storage in to the soil. The LINGRA model has been calibrated and validated using a dataset covering the whole of Great Britain (Qi et al., 2017).

LUCASS (Light Use and Carbon Assimilation in Salix Species) (Cerasuolo et al., 2016) is a process-based growth model for SRC willow. It follows the same principles, simulating the development and growth of SRC at the stand scale, considering sink and source formation and interaction. The organs of the aboveground (leaves, branches, and stems) and below ground (stool and all roots) biomass are considered as sinks, and the C allocation to these sinks is phenologically controlled and balanced with the available carbohydrates. LUCASS can simulate willow roots, stool, dead leaves and litter along with the aboveground biomass. This makes it suitable for this study exploring the changes in aboveground biomass for bioenergy and C storage in to the soil due to different land use. Moreover, not many crop models exist which can simulate willow growth and yield. LUCASS has been calibrated in two locations in the UK, with and without water stress, using C partitioning data for a 2-year rotation following the year of establishment and was validated for two successive 2-year rotations for stem, leaves and stool development (Cerasuolo et al., 2016). It was further validated for final harvest after a 3-year rotation at Rothamsted Research and Long Ashton (southwest England) for the '*Endurance*' and *'Tora'* cultivars (Richard et al., 2019).

AGREMOSA provides options for users to choose different hydrological models: either a physically-based approach (modified Interaction Soil Biosphere Atmosphere, ISBA) based on prognostic equations (Noilhan and Planton, 1989), or, an empirical cascading approach (Burns, 1974) or cascading with travel time (Neitsch et al., 2002). The hydraulic parameters for the hydrological models are internally estimated using the soil-specific van Genuchten parameters provided in the soil database for the study area.

2.5. Tukey's HSD posthoc analysis for the modelled scenarios

To determine if the differences between the outputs for the scenarios were significant, a three-way ANOVA (crop × grid cell × climate) was conducted. Subsequently, the Tukey's honest significant difference (HSD) ($P < 0.05$) *posthoc* test (Tukey, 1977) was performed in the R software environment (R Core Team, 2021) after checking the normality of the data. Finally, all the simulated grid cells were taken together and the significance of difference between the outputs under different land use (crop) and climate was determined by only considering crop and climate interactions in the Tukey's HSD test.

3. Results and discussion

3.1. Net primary productivity and impact of changing climate on above (AGB) and belowground biomass (BGB)

3.1.1. Net primary productivity (NPP) of improved permanent grassland (IPG)

The average NPP of IPG was 19.2 t ha^{-1} for baseline climate which increased by more than a tonne for recent climate (Figs. 3, 4). Higher positive impacts of changing climate were evident on the NPP of IPG in the cooler weather zones (HRM and MRU) (grid cell 5, grid cell 8 which represents cells 6–8, grid cell 9 which represents cells 9–18 and grid cell 20) (Table 1). These results corroborate the findings of Ritchie et al. (2019) who predicted greater impact of climate change on the NPP of grasslands in cooler locations across Great Britain.

In the LRL zones *e.g.,* cells 19 and 31 (both exposed to the same weather but different soils) NPP exhibited a small (3.1 %) increase. Whilst grid cells 20 and 21 have the same soil properties, they fall in different weather zones. Thus, the impact of changing climate on the NPP of IPG in different weather zones is evident with the cooler MRU zone (cell 20) experiencing a higher positive impact compared with the warmer LRL zone (cell 21). Only grid cell 28 manifested a slight negative impact on NPP.

The upper River Taw catchment lies in the southwest and therefore our results accord with previous work. Overall, considering all the simulated cells, the average NPP increased by 5.8 % under the recent climate scenario (Table 1). Both increased temperature and atmospheric CO_2 concentration, have positive effects on grassland, also leading to efficient water use (Soussana and Luscher, 2007; Ritchie et al., 2019) and any reductions in precipitation may not have much impact on the production in this area (Ayling et al., 2021).

Although there was a rise of NPP for IPG due to warming climate, the change was not statistically significant when averaged over all simulated cells ($p < 0.5$; see Table S3).

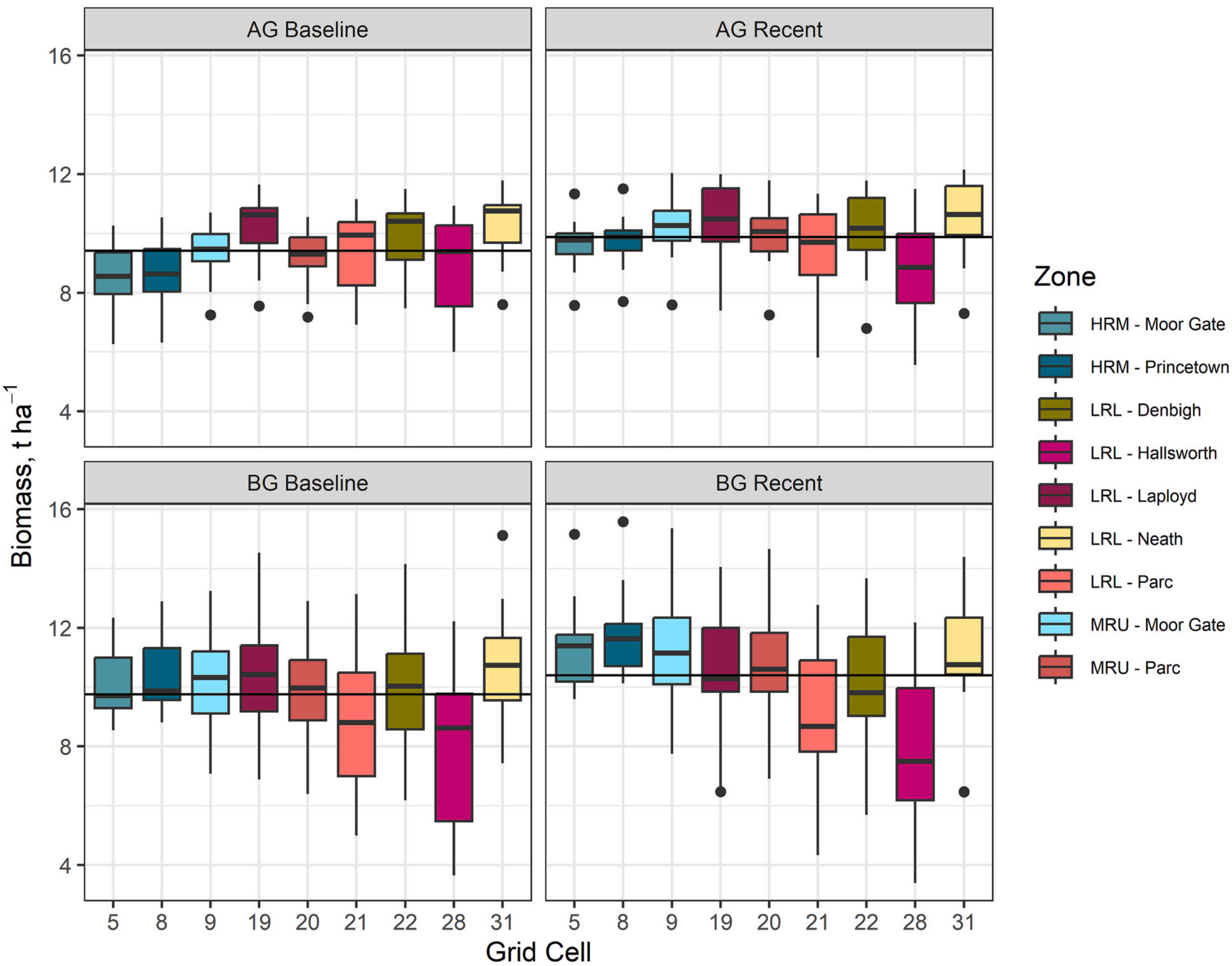


Fig. 3. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for improved permanent grassland (IPG) in different grid cells during baseline and recent climate. The horizontal line shows the overall mean. The weather zone and soil classification are given in the legend. The different weather zones are high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

3.1.2. Partitioning of net primary productivity (NPP) into above and belowground biomass

The impact of changing climate on the allocation of AGB and BGB has implications for energy (Qi et al., 2018) and C sequestration (O'Mara, 2012). The average AGB and BGB for IPG were 9.4 and 9.7 t ha^{-1} for baseline and 9.9 and 10.4 t ha^{-1} for recent climate, respectively (Fig. 3). Overall, the total biomass input to the soil *i.e.,* BGB (to which litter and dead leaves were added) was slightly more positively affected than AGB during recent climate compared to the baseline scenario (Table 2), having favourable implications for improving SOC.

An average grassland biomass production of 8–10 t ha^{-1} has been estimated for the UK and northern Europe (Amon et al., 2007; Rosch et al., 2009; Seppala et al., 2009). The positive impact of climate change on grassland was reported by Qi et al. (2018) who estimated 8.7 t ha^{-1} annual AGB for IPG across the UK by 2010 with a similar recommended N application of 150 kg N ha^{-1} (Defra, 2010). They also projected an average annual AGB of 9.8 t ha^{-1} across the UK by 2050. These previous results and projected future trends align with our new results, given our study area is in southwest England which is wet and warm (Richard et al., 2019) and more conducive to crop production (Ritchie et al., 2019).

More variation from year to year is seen in BGB, for both the baseline and recent climate scenarios, compared to AGB. There were more fluctuations in BGB production for cooler cells (mainly 5 and 8) under both climates compared to AGB; however, this spread was increased in the recent climate scenario (Figs. S2, S3). All of these differences in biomass, whether between AGB and BGB or baseline and recent climate, or their interactions, were not statistically significant at the aggregated level (Table S3). Although the gains are not substantial in absolute terms, the positive trend associated with the impact of changing climate in the study area is evident. The higher benefits in BGB production under grasslands indicates the greater C sequestration potential under changing climate and points to employing grassland when C storage in the soil is the primary goal and LUC is not an option.

3.1.3. Net primary productivity (NPP) of Miscanthus

Miscanthus failed in the cooler upland areas under baseline weather (NPP <50 % compared to lowland, LRL). The warmer recent climate scenario increased NPP by >30 % and 22 % in the moorland and upland zones, respectively. For the lowlands, NPP increased in the range of 15.5 to 16.5 %. Overall simulated cells, the net increase in NPP was ~19 % (Table 1). The positive impact of changing climate on *Miscanthus* was more pronounced in cooler upland areas. This is borne out by the fact that grid cells 20 and 21 had the same soil properties but cell 20 lies in the cooler uplands (MRU) and exhibited a 23.3 % increase in NPP, whereas cell 21 which lies in the warmer lowlands (LRL) had an increase in NPP of 16.5 %. The increase in NPP under the recent climate scenario, compared to the baseline scenario, was statistically significant when aggregating all the simulated cells (Table S3). The average NPP of 17.4 t ha^{-1} for *Miscanthus* ranged from 23.3 t ha^{-1} (cell 31) to 8.1 t ha^{-1} (cell 5–8) under recent climate (Figs. 4, 5), which eliminates the steep, high rainfall slopes from growing *Miscanthus* for economic reasons as well as

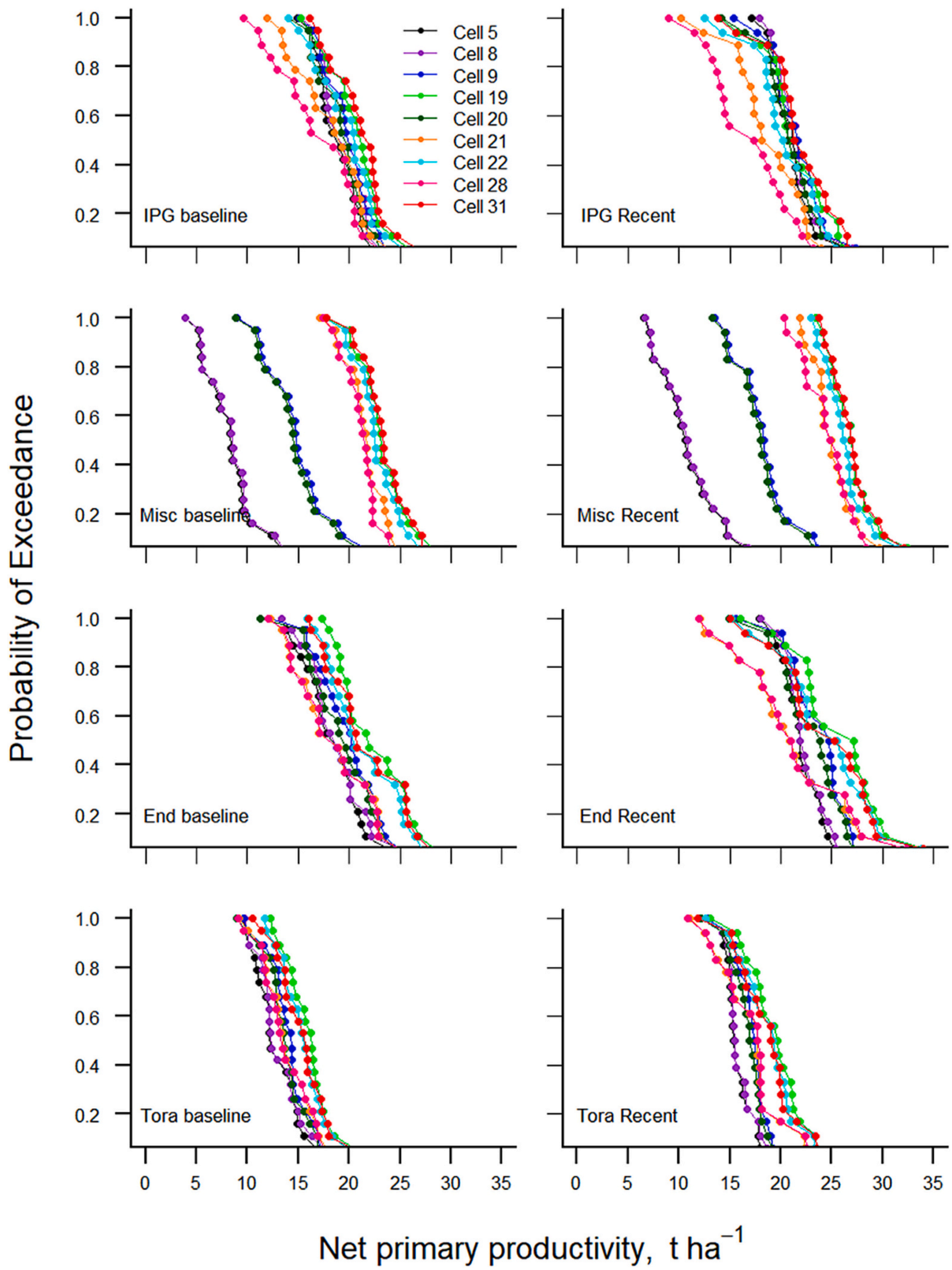


Fig. 4. Probability of exceedance of net primary productivity (NPP) (t ha^{-1}) of different land uses in different grid cells during baseline and recent climate. The different land uses are: improved permanent grassland (IPG), *Miscanthus* (Misc) and the '*Endurance*' (End) and '*Tora*' cultivars of willow.

challenges associated with harvesting. Looking at the probability of exceedance of NPP for *Miscanthus* (Fig. 4) it is clear that temperature acts as an important control in the study environment, where precipitation is not limiting (Heaton et al., 2004).

3.1.4. Partitioning of net primary productivity (NPP) into above and belowground biomass

A statistically significant increase in the AGB of *Miscanthus* was observed, compared to BGB, due to changing climate, when all the simulated cells were considered (Table 2, Table S3). The average AGB and BGB were 9.5 and 8.0 t ha^{-1} for baseline and 12.2 and 8.5 t ha^{-1} for recent climate, respectively (Fig. 5). A belowground to aboveground biomass ratio of 0.54 was reported by Dohleman et al. (2012); however, they only considered the rhizome. In our study, the corresponding ratio is 0.84 and BGM includes roots, rhizome and litter and dead leaves which eventually go to the soil and contribute to soil C. For comparison, Christian et al. (2006), using an experiment conducted at Rothamsted Research in southeast England, reported a ratio of 1.02, wherein litter was included in BGB.

Hastings et al. (2014) modelled *Miscanthus* yield in southwest UK and reported 13.1 t ha^{-1} dry matter for climate in 2011, corroborating our results for the recent climate scenario, albeit with a slight overestimation. They also reported the increasing trend of mean *Miscanthus* dry matter yield from 9.5 t ha^{-1} in 2010 to 11.3 t ha^{-1} in 2050 across the UK, highlighting the positive impact of warming temperatures and increased atmospheric CO_2 levels. Although CO_2 fertilisation may not

Table 1
Mean percentage change in net primary productivity (NPP) of different PBE crops from baseline to recent climate. The weather zones are, high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

Grid Cell	Weather zone	Soil classification	Mean change in NPP (%)			
			IPG	*Miscanthus*	*Willow*	
					Endurance	*Tora*
5	HRM	Moorgate	12.0	31.4	20.5	23.3
8	HRM	Prince town	11.7	30.7	19.2	22.0
9	MRU	Moorgate	8.8	22.7	19.3	22.6
19	LRL	Laployd	3.1	15.8	14.0	20.9
20	MRU	Parc	8.7	23.3	19.3	22.9
21	LRL	Parc	2.0	16.5	14.8	23.1
22	LRL	Denbigh	2.8	16.1	14.4	21.5
28	LRL	Hallsworth	−0.9	16.2	15.3	24.1
31	LRL	Neath	3.1	15.6	12.7	21.4
Average			5.8	18.9	16.5	22.4

Table 2
Mean percentage change in aboveground (AGB) and belowground biomass (BGB) of different PBE crops for baseline and recent climate. The weather zones are high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

Grid Cell	Weather zone	Soil classification	Mean change in AGB (%)				Mean change in BGB (%)			
			IPG	*Miscanthus*	*Willow*		*IPG*	*Miscanthus*	*Willow*	
					Endurance	*Tora*			*Endurance*	*Tora*
5	HRM	Moorgate	11.5	53.2	59.9	51.2	12.5	14.3	8.9	11.3
8	HRM	Prince town	11.4	52.0	56.4	48.7	12.0	13.9	7.9	10.4
9	MRU	Moorgate	7.8	37.1	40.1	40.0	9.7	7.7	6.2	7.1
19	LRL	Laployd	2.6	23.3	18.6	21.3	3.6	6.0	8.3	20.0
20	MRU	Parc	7.6	38.0	40.1	40.4	9.8	8.1	6.3	7.4
21	LRL	Parc	1.3	25.0	19.3	23.4	2.9	5.5	9.5	22.6
22	LRL	Denbigh	2.3	23.8	18.9	21.9	3.4	5.9	9.0	20.7
28	LRL	Hallsworth	−1.9	24.7	19.9	24.3	0.1	5.2	10.1	23.9
31	LRL	Neath	2.4	22.9	18.0	22.1	3.8	5.9	6.3	20.0
Average			4.9	28.7	27.1	29.0	6.6	7.2	7.9	14.6

have significant impact on C4 crops like *Miscanthus*, it could reduce water use and hence increase yield by delaying the onset of any water stress (Hastings et al., 2014; Dixit et al., 2018). An average *Miscanthus* yield of 12.3 t ha^{-1} was reported using a combination of empirical modelling and GIS across England (Lovett et al., 2009) whilst Richter et al. (2008) estimated an overall national average *Miscanthus* yield of 9.6 t ha^{-1} from about 15 million hectares and reported that it is much lower than the average recorded experimental yield of 12.8 t ha^{-1} (with a range of 5 to 18 t ha^{-1}) from 14 experimental stations across the UK. Readers are reminded that these yield estimates are for aboveground only. Thus, our findings for simulated *Miscanthus* AGB in this study are robust and consistent with the range reported in the existing literature.

Under the baseline climate scenario, AGB was predicted to be about the same for *Miscanthus* (9.5 t ha^{-1}) and IPG (9.4 t ha^{-1}), but BGB is ~18 % lower. For the recent climate scenario, *Miscanthus* produces 23 % higher AGB and though the BGB increases by 6 %, the absolute value remains about 18 % lower than that for IPG (8.5 for *Miscanthus* to 10.4 t ha^{-1} for IPG) (Figs. 3, 5). This information is important in setting the priority in the region in relation to the objective of PBE crop production. For biomass production for energy, *Miscanthus* outperforms IPG especially for recent climate, but if C sequestration and more C input to the soil is the primary goal, then IPG performs better in the study area.

For the recent climate scenario, the increase in AGB is 28.7 % compared to just 7.2 % for BGB across all zones. There is more than a 50 % increase in AGB in the cooler moorland and a 37–38 % increase in the upland. In the warmer lowland, the corresponding increase is in the range of 23–25 %. However, the highest increase in BGB, ~14 %, is in the coolest cells in HRM zone, compared with 5.2 to 8.1 % for the rest of the simulated cells in the MRU and LRL zones (Table 2). For AGB, the cool areas would perform well in changing climate. The variation from year to year, for both climate scenarios, is higher for AGB in cooler cells, as warmer cells remain more resilient and consistent (Figs. S2, S3). The impact of extreme climate is not studied here, that might have negative impacts on the production of AGB and BGB. Hager et al. (2014) reported that there has been little investigation of high temperature stress effects on the growth of *Miscanthus* and considered upper growth threshold at 32 °C of a sensitive *Miscanthus* cultivar in a modelling study. Nevertheless, based on this study, it appears that whilst overall greater benefits will be achieved in the study area due to changing climate, the uncertainty will also be higher in the cooler zones.

3.1.5. *Net primary productivity (NPP) of the two SRC- willow cultivars*

The willow cultivars '*Endurance*' (broad leaf) and *'Tora'* (narrow leaf) showed different ranges of increases in NPP during the recent climate scenario, compared to the baseline (Table 1). For '*Endurance*', similar to *Miscanthus* and IPG, a greater positive impact was observed in the cooler cells (as observed by Richard et al., 2019) whereas in the case of *'Tora'*, the impact was similar for all the cells. The average percentage increase in NPP for *'Tora'*, due to changing climate, was greater (22.4 %) than the increases for all other crops. Overall, under baseline climate, '*Endurance*' had a 38 % higher average NPP of 19.5 t ha^{-1}, compared with 14.1 t ha^{-1} for *'Tora'*. Under the warmer recent climate, the NPP rose to 22.9 t ha^{-1} for '*Endurance*', a 33 % increase compared with the 17.2 t ha^{-1} for *'Tora'*. Whilst the absolute NPP is higher for '*Endurance*', the trends of increase due to changing climate are greater in the case of *'Tora'* (Figs. 6, 7). Under the recent climate scenario, higher production but with more pronounced year to year spread can be seen in the probability of exceedance charts, compared to the baseline (Fig. 4). Unlike *Miscanthus* where the HRM zone consistently exhibited lower NPP from year to year, this was not the case for either of the willow cultivars. Similar to our results, Hastings et al. (2014) reported that *Miscanthus* produced higher yields with different yield patterns than SRC willow, which

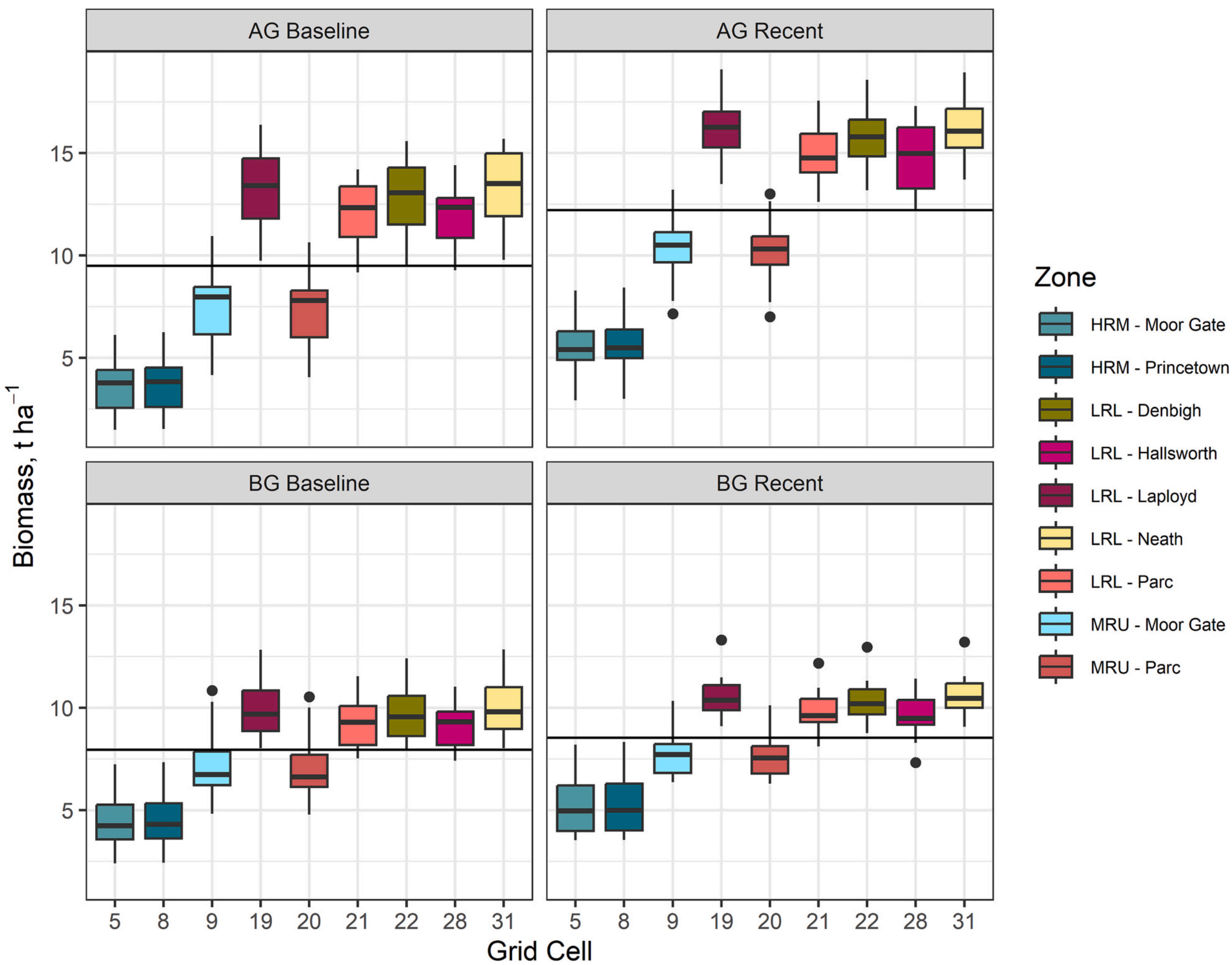


Fig. 5. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for *Miscanthus* in different grid cells during baseline and recent climate. The horizontal line shows the overall mean. The weather zone and soil classification are given in the legend. The different weather zones are high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

performed better in cooler areas. The changes in the NPP of both willow cultivars, from baseline to recent climate, were statistically significant based on the Tukey's HSD *posthoc* test at $p < 0.05$ (Table S3).

3.1.6. Partitioning of net primary productivity (NPP) into above and belowground biomass

The average AGB of '*Endurance*' and *'Tora'* were 8.7 t ha^{-1} and 7.6 t ha^{-1}, respectively, for baseline climate, with increases to 11.1 t ha^{-1} and 9.8 t ha^{-1} for the recent climate scenario (Figs. 6, 7). Thus, the changing climate will favour cultivation of '*Endurance*' due to the increase in AGB compared with the baseline scenario as well as on the basis of the corresponding increase for *'Tora'*.

These results compare well with existing literature. Tallis et al. (2013) reported an annual willow yield of 9.0 t ha^{-1} whereas Hastings et al. (2014) reported a range of 6.1–12.1 t ha^{-1} in the UK with 8.34 t ha^{-1} in the southwest UK for the baseline climate scenario. An expected annual yield of 9 t ha^{-1} for SRC willow was reported for Ireland by Styles et al. (2008). Cunniff et al. (2015) reported annual yield ranges of 9.6–14.6 t ha^{-1} for '*Endurance*' and 9.1–13.1 t ha^{-1} for *'Tora'* in experiments conducted at Harpenden and Aberystwyth in the UK.

These reported yield ranges corroborate our simulations. Further, in the southwest UK, Richard et al. (2019) estimated an increase of 0.7 t ha^{-1} (6.4 %) under recent climate (1990–2014) compared to the baseline (1965–1989) yield of 11.0 t ha^{-1} for '*Endurance*' and an increase of 0.9 t ha^{-1} (8.7 %) from a baseline yield of 10.3 t ha^{-1} for *'Tora'*. Their values are slightly higher than ours because of the higher mean temperatures in their study (9.86 °C for baseline and 9.93 °C for recent climate).

The positive impact of changing climate on AGB in the cooler HRM zone was higher for '*Endurance*' (Table 2). Under cooler climate, the broad-leaf cultivar '*Endurance*' with larger canopies performed better than the narrow leaf cultivar *'Tora'* with smaller canopies in a recent modelling study (Richard et al., 2019). In warmer lowland areas, the percentage increase in *'Tora'* was higher than that for '*Endurance*'. It appears that in cooler areas, the '*Endurance*' cultivar would perform better in terms of exploiting the temperature increases due to a warming climate.

However, this trend of increasing biomass in the cooler HRM was different for BGB. Here, the percent increases due to changing climate, were consistently higher for *'Tora'* compared to '*Endurance*' and the warmer cells in the LRL zone had almost double or higher increases in BGB compared to the cooler cells in the HRM and MRU zones (Table 2). Cunniff et al. (2015) demonstrated that different biomass allocation patterns exist in different willow genotypes and that high BGB does not preclude high AGB. They found that changes in climate, soil properties and resource availability have a stronger and statistically significant impact on biomass allocation patterns than genotypic differences. This explains the different patterns for increases in AGB and BGB for the two different willow cultivars in different pedo-climatic zones in our study catchment.

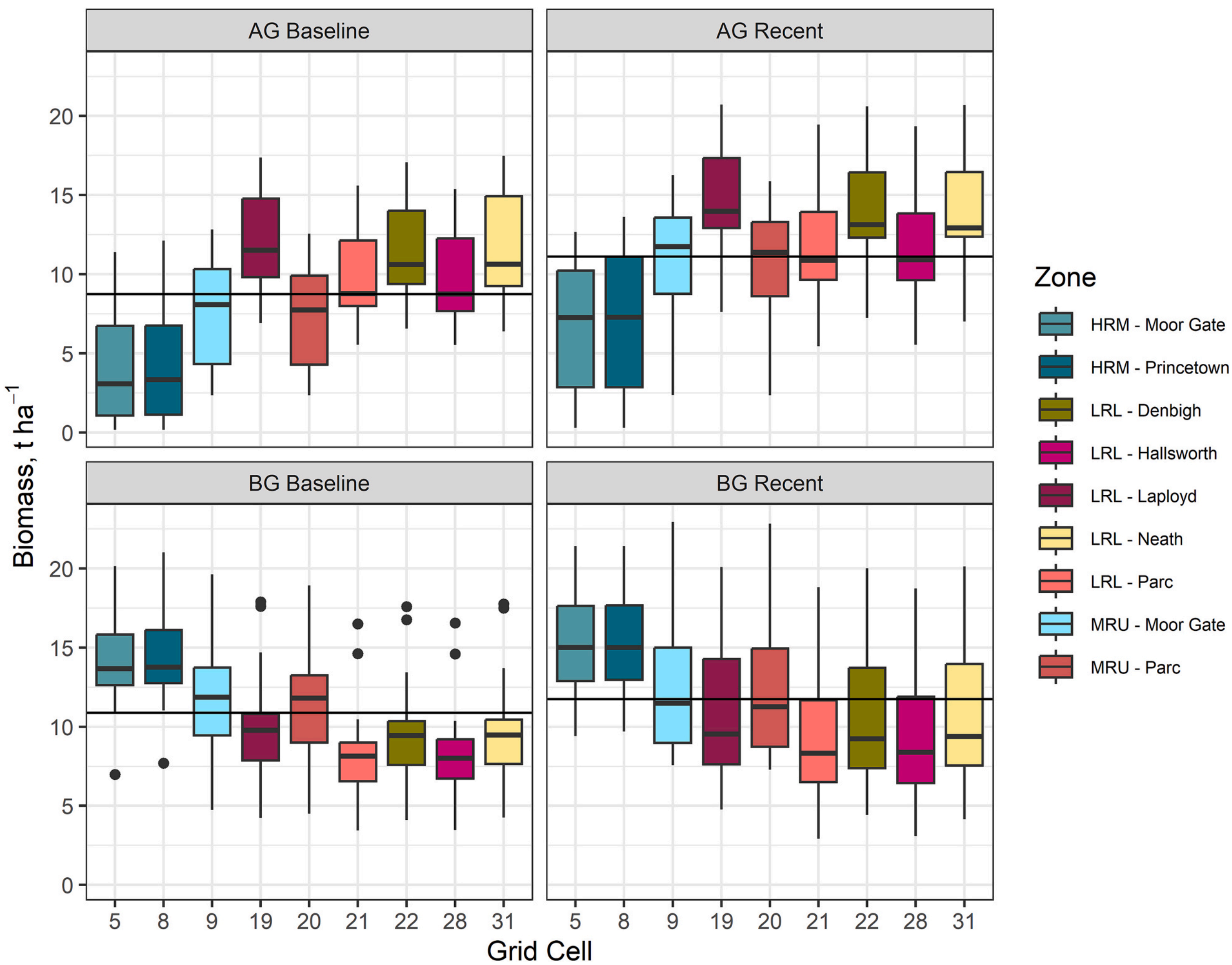


Fig. 6. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for the broad-leaf willow cultivar '*Endurance'* in different grid cells during baseline and recent climate. The horizontal line shows the overall mean. The weather zone and soil classification are given in the legend. The different weather zones are high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

The average BGB of '*Endurance*' for the baseline climate scenario was 10.9 t ha^{-1}; about 68 % higher than the BGB of 6.5 t ha^{-1} for *'Tora'*. The corresponding values increased to 11.7 t ha^{-1} for '*Endurance*' and 7.4 t ha^{-1} for *'Tora'* under the recent climate scenario. This translates into a 58 % greater increase in BGB production for '*Endurance*' compared with *'Tora'* during recent climate. For AGB, the corresponding increases from baseline to recent climate were statistically significant for both '*Endurance*' and *'Tora'*; however, this was not the case for BGB (Table S3). This indicates that the effect of changing climate can be better exploited by using the higher predicted AGB for the '*Endurance*' cultivar, especially in cooler weather zones. However, for a given production, the percentage increases in BGB are higher for *'Tora'* although the absolute value is lower than for the '*Endurance*' cultivar.

The cooler moorland and upland produced lower AGB from year to year but higher BGB as evident from Figs. S2 and S3. *'Tora'* was a bit more resilient than '*Endurance*' from year to year in the case of AGB, although the absolute magnitude was lower. This means that in cooler areas, willow performs best for C sequestration. However, for biomass production for energy, the warmer areas are more favourable. The growth of two desert willow species didn't show any negative impact of upper temperature threshold up to 35 °C (Yang et al., 2004). Although the threshold level of the desert species is likely to be higher than the cultivars in this study, future warming of climate is not expected to negatively impact the production at any stage because the mean temperature in warmer months is <13 °C at the study area during current climate.

Considering all the PBE crops together, the impact of changing climate on the NPP of IPG was small (an increase of 1.1 t ha^{-1}) compared to the corresponding impacts on *Miscanthus* and the Endurance cultivar of willow (both 3.4 t ha^{-1} increase) and on Tora (an increase of 3.1 t ha^{-1}). The % increase in NPP for *Miscanthus* was highest except for the narrow leaf willow cultivar *'Tora'* (which had the lower absolute value). This has implications for the deployment of *Miscanthus* as a PBE crop in changing climate in the region compared to IPG, if NPP is the primary goal.

3.2. Land use change potential for production and C sequestration in a changing climate

For higher NPP, and when considering the effect of changing climate in all three weather zones, the best performing land use change from IPG is the '*Endurance*' cultivar of SRC willow. The benefits of land use change to '*Endurance*' for NPP range from 3–4 % in the colder moorland to 12–27 % in the warmer lowlands (Table 3). '*Endurance*' also performed better than IPG under baseline climate but only in the warmer lowlands. In the uplands, a benefit of >9 % was predicted whereas overall an increase of ~13 % was projected. In the warmer lowlands, however, land use change to *Miscanthus* delivered the highest increase in NPP (24–48 %), during recent climate (Table 3).

Miscanthus performed better in the warmer zone under baseline

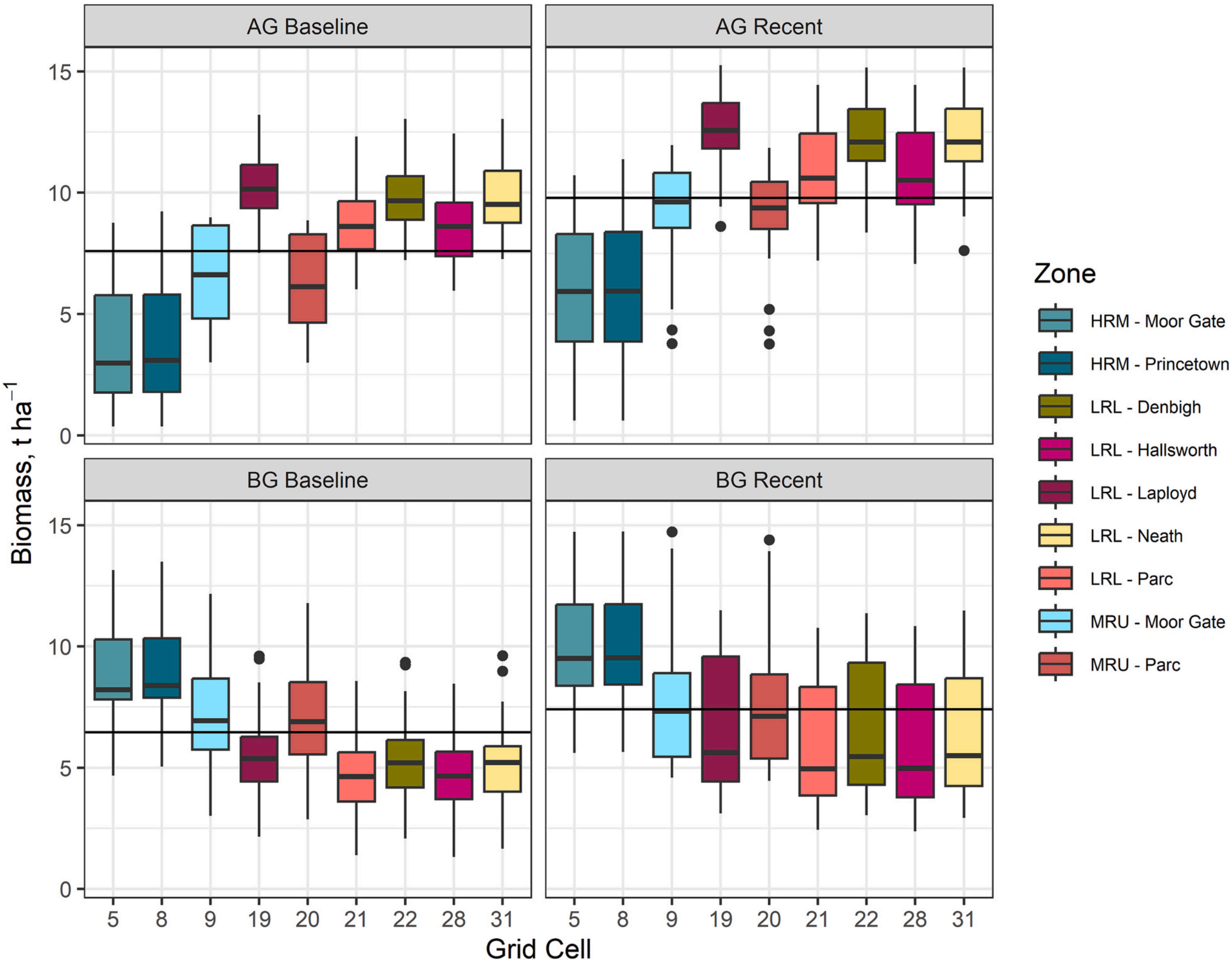


Fig. 7. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for the narrow-leaf willow cultivar '*Tora*' in different grid cells during baseline and recent climate. The horizontal line shows the overall mean. The weather zone and soil classification are given in the legend. The different weather zones are high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

Table 3
Mean percentage change in the net primary productivity (NPP) of *Miscanthus* and willow considering improved permanent grassland (IPG) as the baseline land use. The weather zones are, high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

Grid Cell	Weather zone	Soil classification	Mean change in NPP (%)					
			Miscanthus		*Willow*			
					Endurance		*Tora*	
			Baseline	Recent	Baseline	Recent	Baseline	Recent
5	HRM	Moorgate	−56.7	−49.2	−3.1	4.2	−32.3	−25.5
8	HRM	Prince town	−57.0	−49.7	−3.2	3.3	−32.7	−26.4
9	MRU	Moorgate	−24.9	−15.3	−0.3	9.4	−29.5	−20.6
19	LRL	Laployd	12.9	26.9	8.3	19.8	−22.7	−9.4
20	MRU	Parc	−24.1	−13.9	−0.2	9.4	−29.0	−19.8
21	LRL	Parc	18.3	35.0	0.7	13.4	−24.6	−9.0
22	LRL	Denbigh	14.8	29.5	7.7	19.9	−22.2	−8.0
28	LRL	Hallsworth	26.0	47.8	8.8	26.7	−18.9	1.6
31	LRL	Neath	11.0	24.4	2.4	11.9	−27.5	−14.7
Average			−9.0	2.3	2.3	12.7	−26.7	−15.2

climate, compared to IPG, but this increase was almost doubled in the recent climate scenario. In the cooler zones (HRM and MRU) of the study area, however, IPG performed better and either *Miscanthus* or any willow cultivar failed to perform well during baseline climate. *'Tora'* performed worst in both climates, albeit comparatively better under recent climate, with a few exceptions in cooler cells where the decrease in NPP was less than *Miscanthus*. The NPP reduced to about 49–50 % (HRM zone) and 14–15 % (MRU zone) for *Miscanthus* and about 26 % (HRM zone) and 20–21 % (MRU zone) for *'Tora'* under recent climate when land use was changed from IPG. On this basis, it can therefore be recommended that in cooler cells (or by extension, cooler regions in other parts of the country) land use practice should shift to the broad leaf willow cultivar '*Endurance*' for delivering the highest NPP, whereas in warmer areas, growing *Miscanthus* should be practiced. These findings conform with the results of Hastings et al. (2014). Clearly, the impacts of both changing climate and land use have potential to enhance NPP in the upper River Taw study catchment.

Looking into the partitioning of potentially newly established PBE crops into AGB and BGB (Table 4), there is always a decrease of AGB in moorland for *Miscanthus* under both baseline and recent climate and a slight increase of ~2 % in the cooler uplands under recent climate.

'*Tora*' failed to perform well and consistently provided lower AGB and BGB and is not a suitable alternative in the study catchment either for bioenergy production or C sequestration. This result could also be extended to other narrow leaf willow cultivars which are similar to '*Tora*'. In the cooler moorland and upland zones of the study catchment, the broad leaf willow cultivar '*Endurance*' produced higher BGB than AGB under both climates and so is more suitable for C sequestration and improvement of soil health which could further aid the production as well as C sequestration potential (Gallardo and Bond, 2011). A study by Styles and Jones (2007) showed that SRC willow and *Miscanthus* can have the same amount of underground C storage as grassland systems and Clarke et al. (2019) found that pasture conversion to SRC willow had a net emission rate of C from soils, whereas the C stored in *Miscanthus* soils was greater than that of pasture lands which was consistent with the findings reported by Lal (2009) and Harris et al. (2015). Their results showed *Miscanthus* has a higher capacity for SOC storage than pasture lands corroborating with our results for the lowland portion of the study area. However, it is reported that LUC to PBE production in Europe from grassland to *Miscanthus* will have a small effect on SOC (Don et al., 2012). In contrast, Zatta et al. (2014) reported that planting a range of *Miscanthus* genotypes on semipermanent grasslands did not deplete SOC significantly after 6 years from establishment. Several studies found no significant change in SOC following the conversion of grassland to *Miscanthus* (Clifton-Brown et al., 2007; Schneckenberger and Kuzyakov, 2007) and a loss of SOC following land use change from grassland to *Miscanthus* and SRC willow (Qin et al., 2016; Jug et al., 1999; Makeschin, 1994). Similar to our results, Yang et al. (2020) found that the willow crops are a biomass feedstock that is carbon-negative across the landscape when it is grown on land that was formerly in cropland/pasture, indicating their potential for climate change mitigation. Such findings are reported because the amount of SOC sequestered in the soil is a function of site-specific factors including soil texture, management practices, initial SOC levels and climate; for these reasons, both losses and gains in SOC have been reported by previous studies of LUC to *Miscanthus* and SRC willow (Dondini et al., 2016; Hansen et al., 2004; Lemus and Lal, 2005; Clifton-Brown et al., 2007).

3.3. Implications of land use change and changing climate for changes in SOC

Different components of belowground biomass affect SOC differently that is controlled by the decay rate of plant material on the surface (dead leaves and litter) and the root growth below the surface. These include the rhizome in IPG and *Miscanthus* and the stools in the case of willow (Garten et al., 2011; Harris et al., 2015; Murphy et al., 2014). For IPG, all the components of BGB manifested almost no difference in their proportions to total BGB under the climate change scenarios. Although the amount of roots increased by about 8 %, rhizome by 21.5 % and dead leaves by 5.5 % (Fig. 8) considering all the zones in the study area.

For *Miscanthus*, the changes in the proportion of BGB components to the total BGB were as follows: the roots proportion decreased from 12.6 to 10.8 %, rhizome decreased from 11.7 to 10.4 % and dead leaves increased from 75.7 to 78.8 %. As the amount of roots decreased by 8 % and rhizome by 5 %, the dead leaves increased by 11.7 % (Fig. 8). Dead leaves and litter input to the soil play an important role in sequestering C in a mature crop (Lewandowski et al., 2000; Clifton-Brown et al., 2004). Whilst it accounts for most of the reduction in yield during ripening, it is a gain for soil organic matter and C.

The proportion of roots for '*Endurance*' increased from 58 to 63 %, dead leaves from 34.5 to 36 % and the proportion of stool decreased from 7.2 to <1 %. For '*Tora*' the proportion of roots increased from 64.6 to 66.9 % and dead leaves from 28.1 to 32.7 %, whereas the proportion of stool decreased from 7.3 to 1.3 %. In the case of '*Endurance*', the amount of roots increased by 17 % and dead leaves by 29 %, whereas the amount of stool decreased by 89 %. For '*Tora*', the roots increased by 18.7 % and dead leaves by 13 %, whereas the stool decreased by 79 % (Fig. 8). These results are corroborated by the experiments conducted by Cunniff et al. (2015) where they measured the roots and stool of the '*Endurance*' cultivar of willow at two locations, Harpenden and Aberystwyth. Harpenden had the higher monthly maximum temperatures and photosynthetically active radiation of the two sites and produced higher mass and proportion of roots and lower mass and proportion of stool compared to Aberystwyth. Overall, the increased proportions of roots, along with their absolute values, for willows, favour willow over *Miscanthus* and IPG for C sequestration, especially as the climate warms up.

The IPG was simulated to produce the highest number of dead leaves (litter was added to dead leaves) followed by *Miscanthus*, '*Endurance*' and '*Tora*'. The willows produced the highest amount of roots with '*Endurance*' being higher than '*Tora*' which increased due to the warming under the recent climate compared to the baseline. Stool production decreased for both willow cultivars as the climate changes. For each cell of the study area, the BGB increased for all the crops during recent climate. This indicates that as the climate is forecast to get

Table 4
Mean percentage change in above (AGB) and below ground biomass (BGB) of *Miscanthus* and willow considering improved permanent grassland (IPG) as the baseline land use.

Grid Cell	Weather zone	Soil classification	Mean change in AGB (%)						Mean change in BGB (%)					
			Miscanthus		*Willow*				*Miscanthus*		*Willow*			
					Endurance		Tora				Endurance		Tora	
			Baseline	Recent	Baseline	Recent	Baseline	Recent	Baseline	Recent	Baseline	Recent	Baseline	Recent
5	HRM	Moorgate	−58.8	−43.5	−52.2	−31.4	−56.1	−40.4	−54.9	−54.1	39.0	34.6	−12.0	−12.9
8	HRM	Prince town	−58.5	−43.4	−50.6	−30.6	−55.3	−40.3	−55.7	−55.0	36.7	31.7	−13.6	−14.8
9	MRU	Moorgate	−20.0	1.8	−19.4	4.8	−30.9	−10.3	−29.5	−30.7	17.4	13.7	−28.2	−29.9
19	LRL	Laployd	29.0	55.0	19.4	38.1	0.5	18.9	−3.1	−0.9	−2.6	1.7	−45.8	−37.3
20	MRU	Parc	−20.4	2.2	−20.9	3.0	−31.4	−10.5	−27.6	−28.7	19.2	15.4	−26.8	−28.3
21	LRL	Parc	28.7	58.8	5.8	24.6	−5.3	15.4	7.1	9.8	−4.7	1.5	−45.3	−34.9
22	LRL	Denbigh	29.1	56.4	17.1	36.1	0.1	19.3	0.1	2.5	−1.8	3.5	−44.8	−35.6
28	LRL	Hallsworth	34.2	70.6	10.6	35.1	−0.9	25.5	16.7	22.6	6.7	17.3	−39.4	−25.0
31	LRL	Neath	28.8	54.5	13.9	31.2	−4.1	14.4	−6.2	−4.3	−8.7	−6.5	−50.2	−42.4
Average			0.7	23.6	−7.2	12.5	−19.4	−0.9	−18.3	−17.9	11.6	12.9	−33.7	−28.8

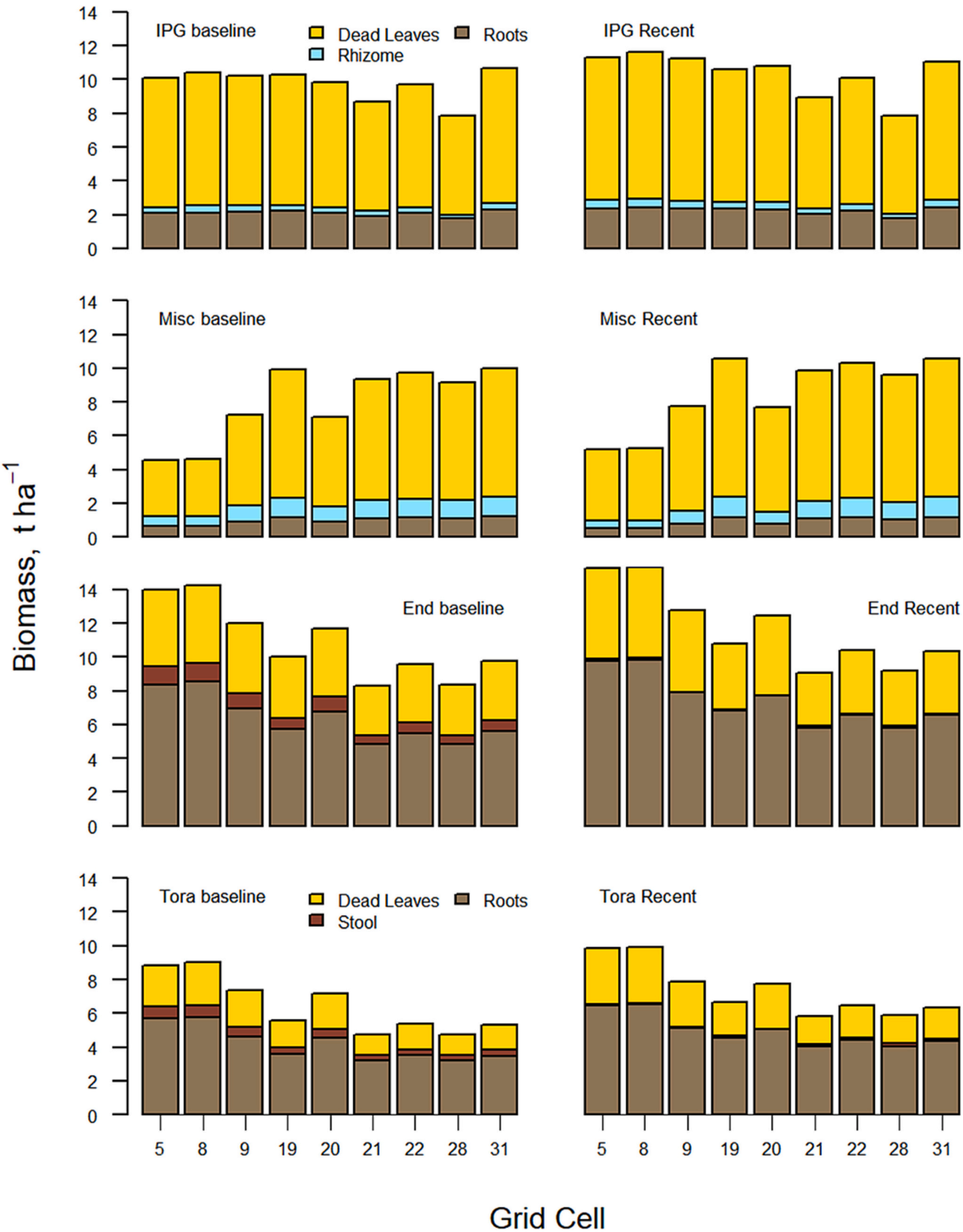


Fig. 8. Belowground biomass components (t ha^{-1}) of different land uses in different grid cells during baseline and recent climate. The different land uses are: Improved permanent grassland (IPG), *Miscanthus* (Misc) and the '*Endurance*' (End) and '*Tora*' cultivars of willow.

warmer, positive impacts will be observed on C sequestration under all land uses. Subtle changes are predicted for the rhizome and roots of IPG and *Miscanthus* as the climate changes. The roots of PBE crops persist longer than those of annual crops, which is important because SOC is primarily derived from roots (Blanco-Canqui, 2016; Rasse et al., 2005).

However, roots need to turn over to be incorporated into SOC, in order to contribute to C sequestration (Gregory et al., 2018). Stools take longer to decompose and hence the changing climate favours the decomposition of BGB by means of lower stool and higher root production. Thus, changing climate not only increases plant biomass input to the soil but also potentially aids the increase of SOC, thereby improving soil health more generally.

Agostini et al. (2015) found that inputs from fine root C stocks were greater for willow (1.0 t ha^{-1} $year^{-1}$) than *Miscanthus* (0.5 t ha^{-1} $year^{-1}$). Thus, their results are very similar to ours for *Miscanthus*, considering 43 % of C in root biomass; however, our simulated willow root C stocks are higher. For the contribution to SOC stock changes, it is important to consider that willow roots have a shorter mean residence time (1.3 years) than *Miscanthus* (1.8 years) and the finer nature of willow roots accelerates their turnover (Gregory et al., 2018). The actual contribution to improving soil C is a function of higher inputs and faster turnover rate under changing climate. However, the larger amount of *Miscanthus* dead leaves and their predicted increase due to changing climate might compensate the amount of C in the soil, meaning both the *Miscanthus* and '*Endurance*' will contribute to SOC. In general, fresh and easily decomposable matter, like fine roots and leaves, have a slightly smaller biomass C fraction (43 %) than woody material like the stool (46 %) (Agostini et al., 2015; Martini et al., 2020) and have a faster turnover thereby contributing to SOC faster than structural components (Rytter, 2012). The predicted decrease in the stool under changing climate will not affect SOC much because the amount of stool production is low and, regardless, it takes longer to be incorporated into the soil. Root biomass of 4.1 t ha^{-1} under a 5- year stand of *Miscanthus* was reported in northern France (Ferchaud et al., 2016) which is similar to our climatic conditions and 2.9–7.1 t ha^{-1} for the UK in a 4 to 6 year study (Gregory et al., 2018). These values corroborate with our findings of simulated root biomass of about 0.92 t ha^{-1} per year.

C input to the soil may be important when willow is coppiced as increased root turnover may follow harvesting of AGB (Don et al., 2012). On this basis, our predicted increase in roots due to changing climate in the case of willow, could contribute to higher C inputs to the soil unlike *Miscanthus*, where the impact of changing climate is negative on root biomass accumulation.

Fig. 8 shows that the major changes in belowground components, along with the total BGB (Table 4), are only predicted for the willow cultivar '*Endurance*' when we shift the land use from IPG. Whilst the BGB increased due to changing climate, the easily decomposable components; roots and dead leaves also increased and the comparatively slow-decomposable component (stool) decreased. Importantly, this would translate into higher SOC in a shorter period of time as the climate changes. Thus, the willow would have a greater contribution to the percentage of BGB converted into SOC, directly affecting soil health favourably.

4. Conclusions

The changing climate, based on the climate scenarios in this study, is predicted to positively impact the aboveground productivity and belowground biomass input to the soil of all PBE crops in the upper River Taw catchment, southwest England. However, the impact of extreme climate that might have negative impacts on the crop production is not studied here. The absolute increase in NPP of IPG was small compared to *Miscanthus* and both cultivars of willow. *Miscanthus* and '*Endurance*' had the highest absolute increase in NPP followed by '*Tora*', which exhibited the greatest relative improvement. Colder areas at higher elevation are predicted to benefit from changing climate in terms of AGB and BGB for both *Miscanthus* and willow. Both AGB for bioenergy and BGB to enhance C sequestration can be well managed in the context of changing climate by careful selection of a PBE crop and targeted deployment in specific climatic zones. However, this can only be achieved if the C losses from land conversion itself do not exceed the benefits from LUC. For the entire study area, *Miscanthus* is best suited in terms of bioenergy production compared to willow and grassland whereas the broadleaf willow cultivar '*Endurance*' is best suited for C sequestration, among all crops considered, with more C input to the soil from easily decomposable root production. When the land use changes from IPG, and especially so during the recent climate, the potential of '*Endurance*' for C sequestration increases. In the warmer lowland zone, *Miscanthus* is the better performing LUC from IPG whereas, in the cooler upland and moorland zones, '*Endurance*' is the best LUC for enhancing NPP among all crops considered. Except for the '*Endurance*' cultivar of SRC willow, no crop is better than IPG for C sequestration under both climate scenarios. These results are helpful in strategizing sustainable LUC to *Miscanthus* or willow for higher bioenergy production and C sequestration potential in geographies with similar environment conditions to the study area.

CRediT authorship contribution statement

Prakash N. Dixit: Conceptualization, Methodology, Data curation, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing, Project administration. **Goetz M. Richter:** Methodology, Software, Formal analysis, Investigation, Resources, Writing – review & editing, Project administration, Supervision. **Kevin Coleman:** Writing – review & editing, Project administration. **Adrian L. Collins:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

Rothamsted Research receives strategic support from the UKRI-BBSRC (UK Research and Innovation-Biotechnology and Biological Sciences Research Council). This research was supported by the Institute Strategic Programme (ISP) grants BBS/E/C/000I0330 (Soils to Nutrition) and BB/X010961/1 (Resilient Farming Futures). Met data for North Wyke was supplied by the e-RA database, part of the Rothamsted Long-term Experiments National Capability (LTENC), supported by the UK-BBSRC (BBS/E/C/000J0300) and the Lawes Agricultural Trust. The North Wyke Farm Platform is a UK National Capability funded by grant awards BBS/E/C/000J0100 and BB/CCG2280/1. Special thanks go to Jonah Prout, Soil Carbon Modeller/Data Scientist and Marko Stojanovic, Spatial Data Analyst, Rothamsted Research, Harpenden.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166390.

References

Agostini, F., Gregory, A.S., Richter, G.M., 2015. Carbon sequestration by perennial energy crops: is the jury still out? BioEnergy Res. 8, 1057–1080.
AHDB, 2014. The Home-Grown Forage Directory. AHDB, UK.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration —guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization, Rome.
Amon, T., Amon, B., Kryvoruchko, V., Machmüller, A., Hopfner-Sixt, K., Bodiroza, V., Hrbek, R., Friedel, J., Pötsch, E., Wagentristl, H., Schreiner, M., Zollitsch, W., 2007. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. Bioresour. Technol. 17, 3204–3212.
Ayling, S.M., Thompson, J., Gray, A., McEwen, L.J., 2021. Impact of reduced rainfall on above ground dry matter production of semi-natural grassland in south Gloucestershire, UK: a rainfall manipulation study. Front. Environ. Sci. 9, 519 (Article 686668).
BEIS (Department for Business Energy & Industrial Strategy), 2018. UK energy in brief. Retrieved from. https://www.gov.uk/government/statistics/uk-energy-in-brief-2018.
Blanco-Canqui, H., 2016. Growing dedicated energy crops on marginal lands and ecosystem services. Soil Sci. Soc. Am. J. 80 (4), 845–858.
Britt, C.P., Buckland, M., Heath, M.C., 1995. Arable energy coppice. A review of published R&D and discussion of the potential for production on surplus agricultural land in the UK. In: ADAS Report for the Ministry of Agriculture, Fisheries and Food (170 pp.).
Burns, I.G., 1974. A model for predicting the redistribution of salts applied to fallow soils after excess rainfall or evaporation. Eur. J. Soil Sci. 25, 165–178.
CEH, 2017. Integrated Hydrological Digital Terrain Model [IHDTM]. https://catalogue.ceh.ac.uk/documents/242384d6-ce65-4360-bf4e-3f6b4ed53034 (accessed 19th June 2023).
Cerasuolo, M., Richter, G.M., Richard, B., Cunniff, J., Girbau, S., Shield, I., Purdy, S., Karp, A., 2016. Development of a sink-source interaction model for the growth of short-rotation coppice willow and in silico exploration of genotype x environment effects. J. Exp. Bot. 67 (3), 961–977.
Christian, D.G., Poulton, P.R., Riche, A.B., Yates, N.E., Todd, A.D., 2006. The recovery over several seasons of ^{15}N-labelled fertilizer applied to *Miscanthus x giganteus* ranging from 1 to 3 years old. Biomass Bioenergy 30, 125–133.
Clarke, R., Sosa, A., Murphy, F., 2019. Spatial and life cycle assessment of bioenergy-driven land-use changes in Ireland. Sci. Total Environ. 664, 262–275.
Clifton-Brown, J.C., Stampfl, P.F., Jones, M.B., 2004. *Miscanthus* biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. Glob. Chang. Biol. 10, 509–518.
Clifton-Brown, J.C., Breuer, J., Jones, M.B., 2007. Carbon mitigation by the energy crop, *Miscanthus*. Glob. Chang. Biol. 13, 2296–2307.
COP 26, 2021. The 26th Session of the Conference of the Parties (COP 26) to the UNFCCC. 31 October - 12 November, 2021. Glasgow, Scotland, UK.
Cunniff, J., Purdy, S.J., Barraclough, T.J., Castle, M., Maddison, A.L., Jones, L.E., Shield, I.F., Gregory, A.S., Karp, A., 2015. High yielding biomass genotypes of willow (*Salix* spp.) show differences in below ground biomass allocation. Biomass Bioenergy 80, 114–127.
Dass, P., Houlton, B.Z., Wang, Y., Warlind, D., 2018. Grasslands may be more reliable carbon sinks than forests in California. Environ. Res. Lett. 13, 074027.
DECC, 2012. UK Bioenergy Strategy. Department of Energy and Climate Change, London: DECC, pp. 22–24.
DEFRA, 2001. Planting and growing *Miscanthus*. In: Best Practice Guidelines for Applicants to Defra's Energy Crops Scheme. UK Government Department for Environment, Food and Rural Affairs, London.
DEFRA, 2002. Growing short rotation coppice. In: Best Practice Guidelines for Applicants to Defra's Energy Crops Scheme. UK Government Department for Environment, Food and Rural Affairs, London.
DEFRA, 2010. Fertiliser Manual, 8th edition. DEFRA, London/UK.
DEFRA, 2016. Agriculture in the United Kingdom 2015. London/UK.
Dixit, P.N., Telleria, R., Al Khatibb, A.N., Allouzi, S.F., 2018. Decadal analysis of impact of future climate on wheat production in dry Mediterranean environment: a case of Jordan. Sci. Total Environ. 610–611C, 219–233.
Dohleman, F.G., Heaton, E.A., Arundale, R.A., Long, S.P., 2012. Seasonal dynamics of above- and below-ground biomass and nitrogen partitioning in *Miscanthus* × *giganteus* and *Panicum virgatum* across three growing seasons. GCB Bioenergy 4 (5), 534–544.
Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M.S., Drewer, J., Flessa, H., Freibauer, A., Hyvonen, N., Jones, M.B., Lanigan, G.J, Mander, U.,Monti, A., Djomo, S.N., Valentine, J., Walter, K., Zegada-Lizarazu, W., Zenone, T., 2012. Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. GCB Bioenergy, 4(4), 372–391.
Dondini, M., Richards, M., Pogson, M., Jones, E.O., Rowe, R.L., Keith, A.M., McNamara, N.P., Smith, J.U., Smith, P., 2016. Evaluation of the ECOSSE model for simulating soil organic carbon under *Miscanthus* and short rotation coppice-willow crops in Britain. GCB Bioenergy 8 (4), 790–804.
Ferchaud, F., Vitte, G., Mary, B., 2016. Changes in soil carbon stocks under perennial and annual bioenergy crops. GCB Bioenergy 8 (2), 290–306.
Gallardo, A.L.C.F., Bond, A., 2011. Investigating the effectiveness of environmental assessment of land use change: a comparative study of the approaches taken to perennial biomass crop planting in São Paulo and England. Biomass Bioenergy 35, 2285–2297.
García-Freites, S., Gough, C., Röder, M., 2021. The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target. Biomass Bioenergy 151, 106164.
Garten, C.T., Wullschleger, S.D., Classen, A.T., 2011. Review and model-based analysis of factors influencing soil carbon sequestration under hybrid poplar. Biomass Bioenergy 35 (1), 214–226.
van Genuchten, M.T., 1980. A closed form equation for predicting the hydraulic conductivity of 425 unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.
Glasgow Climate Pact, 2021. The Conference of the Parties serving as the meeting of the Parties to the Paris Agreement. Glasgow, p. 3. Archived (PDF) from the original on 15 November 2021. Retrieved 19 November 2021. Avaialble at: https://unfccc.int/sites/default/files/resource/cma3_auv_2_cover%20decision.pdf.
Glithero, N.J., Wilson, P., Ramsden, S.J., 2013. Prospects for arable farm uptake of short rotation coppice willow and *Miscanthus* in England. Appl. Energy 107, 209–218.
Goudriaan, J., van Laar, H.H., 1994. Modelling Potential Crop Growth Processes. Textbook with Exercises. Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 238.
Gov.uk, 2021. https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2020/summary (Accessed 21 Jun, 2014).
Gregory, A.S., Dungait, J.A.J., Shield, I.F., Macalpine, W.J., Cunniff, J., Durenkamp, M., White, R.P., Joynes, A., Richter, G.M., 2018. Species and genotype effects of bioenergy crops on root production, carbon and nitrogen in temperate agricultural soil. BioEnergy Res. 11 (2), 382–397.
Grogan, P., Matthews, R., 2002. A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. Soil Use Manag. 18, 175–183.
Hager, H.A., Sinasac, S.E., Gedalof, Z., Newman, J.A., 2014. Predicting potential global distributions of two miscanthus grasses: implications for horticulture, biofuel production, and biological invasions. PLoS One 9 (6), e100032.
Hansen, E.M., Christensen, B.T., Jensen, L.S., Kristensen, K., 2004. Carbon sequestration in soil beneath long-term *Miscanthus* plantations as determined by C-13 abundance. Biomass Bioenergy 26, 97–105.
Harayama, H., Uemura, A., Utsugi, H., Han, Q., Kitao, M., Maruyama, Y., 2020. The effects of weather, harvest frequency, and rotation number on yield of short rotation coppice willow over 10 years in northern Japan. Biomass Bioenergy 142, 105797.
Harris, Z.M., Spake, R., Taylor, G., 2015. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. Biomass Bioenergy 82, 27–39.
Hassall, K.L., Coleman, K., Dixit, P.N., Granger, S.J., Zhang, Y., Sharp, R.T., Wu, L., Whitmore, A.P., Richter, G.M., Collins, A.L., Milne, A.E., 2022. Exploring the effects of land management change on productivity, carbon and nutrient balance: application of a hierarchical modelling approach to the Upper River Taw Observatory, UK. Sci. Total Environ. 824, 153824.
Hastings, A., Tallis, M.J., Casella, E., Matthews, R.W., Henshall, P.A., Milner, S., Smith, P., Taylor, G., 2014. The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates. GCB Bioenergy 6, 108–122.
Hazard, L., Betin, M., Molinari, N., 2006. Correlated response in plant height and heading date to selection in perennial ryegrass populations. Agron. J. 98, 1384–1391.
Heaton, E., Voigt, T., Long, S.P., 2004. A quantitative review comparing the yields of two candidate C-4 perennial biomass crops in relation to nitrogen, temperature and water. Biomass Bioenergy 27, 21–30.
Heaton, E.A., Dohleman, F.G., Fernando Miguez, A., Juvik, J.A., Lozovaya, V., Widholm, J., Zabotina, O.A., McIsaac, G.F., David, M.B., Voigt, T.B., Boersma, N.N., Long, S.P., 2010. *Miscanthus*: a promising biomass crop. Adv. Bot. Res. 56, 75–136.
Hoglind, M., Schapendonk, A., Van Oijen, M., 2001. Timothy growth in Scandinavia: combining quantitative information and simulation modelling. New Phytol. 151 (2), 355–367.
Isebrands, J.G., Host, G.E., Bollmark, L., Porter, J.R., Philippot, S., Stevens, E., Rushton, K., 1996. A strategy for process modelling of short rotation Salix coppice plantations. Biomass Bioenergy 11, 245–252.
Jorgensen, U., 2011. Benefits versus risks of growing biofuel crops: the case of *Miscanthus*. Curr. Opin. Environ. Sustain. 3, 24–30.
Jug, A., Hofmann-Schielle, C., Makeschin, F., Rehfuess, K.E., 1999. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany II. Nutritional status and bioelement export by harvested shoot axes. For. Ecol. Manag. 121, 67–83.
Lal, R., 2009. Soil quality impacts of residue removal for bioethanol production. Soil Tillage Res. 102 (2), 233–241.
Lemus, R., Lal, R., 2005. Bioenergy crops and carbon sequestration. Crit. Rev. Plant Sci. 24, 1–21.
Lewandowski, I., Clifton-Brown, J.C., Scurlock, J.M.O., Huisman, W., 2000. *Miscanthus*: European experience with a novel energy crop. Biomass Bioenergy 19, 209–227.
Lewandowski, I., Scurlock, J.M.O., Lindvall, E., Christou, M., 2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 25, 335–361.
Lovett, A.A., Sünnenberg, G.M., Richter, G.M., Dailey, A.G., Riche, A.B., Karp, A., 2009. Biomass production and land use trade-offs revealed by GIS constraint and yield mapping of *Miscanthus* in England. BioEnergy Res. 2, 17–29.
Lovett, A., Sunnenberg, G., Dockerty, T., 2014. The availability of land for perennial energy crops in Great Britain. GCB Bioenergy 6, 99–107.
Makeschin, F., 1994. Effects of energy forestry on soils. Biomass Bioenergy 6, 63–79.
Martini, E., Ferrarini, A., Serra, P., Pilla, M., Marcone, A., Amaducci, S., 2020. Belowground biomass C outweighs SOC of perennial energy crops: insights from a long-term multispecies trial. GCB Bioenergy 13, 459–472.
McCalmont, J.P., McNamara, N.P., Donnison, I.S., Farrar, K., Clifton-Brown, J.C., 2017. An interyear comparison of CO_2 flux and carbon budget at a commercial-scale land-use transition from semi-improved grassland to *Miscanthus x giganteus*. GCB Bioenergy 9 (1), 229–245.
Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.-F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M.,

van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentra-tions and their extensions from 1765 to 2300. Clim. Chang. 109, 213–241.
Murphy, F., Devlin, G., McDonnell, K., 2013. *Miscanthus* production and processing in Ireland: an analysis of energy requirements and environmental impacts. Renew. Sustain. Energy Rev. 23, 412–420.
Murphy, F., Devlin, G., McDonnell, K., 2014. Energy requirements and environmental impacts associated with the production of short rotation willow (*Salix* sp.) chip in Ireland. GCB Bioenergy 6 (6), 727–739.
Nakajima, T., Yamada, T., Anzoua, K.G., Kokubo, R., Noborio, K., 2018. Carbon sequestration and yield performances of *Miscanthus x giganteus* and *Miscanthus sinensis*. Carbon Manag. 9, 415–423.
Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2002. Soil and Water Assessment Tool. Theoretical Documentation. Published by Texas Water Resources Institute, College Station, Texas (TWRI Report TR-191.).
Ni, Y.Z., Mwabonje, O.N., Richter, G.M., Qi, A.M., Yeung, K., Patel, M., Wood, J., 2019. Assessing availability and greenhouse gas emissions of lignocellulosic biomass feedstock supply - case study for a catchment in England. Biofuels Bioprod. Biorefin. 13, 568–581.
Noilhan, J., Planton, S., 1989. A simple parameterization of land surface processes for meteorological models. Monthly Weather Reviews 117, 536–549.
O'Mara, F.P., 2012. The role of grasslands in food security and climate change. Ann. Bot. 110, 1263–1270.
Qi, A.M., Murray, P.J., Richter, G.M., 2017. Modelling productivity and resource use efficiency for grassland ecosystems in the UK. Eur. J. Agron. 89, 148–158.
Qi, A., Holland, R.A., Taylor, G., Richter, G.M., 2018. Grassland futures in Great Britain-productivity assessment and scenarios for land use change opportunities. Sci. Total Environ. 634, 1108–1118.
Qin, Z., Dunn, J.B., Kwon, H., Mueller, S., Wander, M.M., 2016. Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. GCB Bioenergy 8, 66–80.
R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL. https://www.R-project.org/.
Rasse, D.P., Rumpel, C., Digna, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269, 341–356.
REA, 2021. Bioenergy in the UK: A Vision to 2032 and Beyond. Renewable Energy Association, London: REA, pp. 18–20.
Richard, B., Richter, G.M., Cerasuolo, M., Shield, I., 2019. Optimizing the bioenergy water footprint by selecting SRC willow canopy phenotypes: regional scenario simulations. Ann. Bot. 124 (4), 531–542.
Richter, G.M., Rana, G., Ferrara, R.M., Ventrella, D., Acutis, M., Trevisiol, P., Mayr, T., Baggaley, N., Morris, J., Holmes, A., Trawick, P., Dailey, A.G., Robbins, P., Simota, C., Whitmore, A.P., Powlson, D.S., 2006. Stability and Mitigation of Arable Systems in Hilly Landscapes Final Report. European Commission, Brussels, p. 280.
Richter, G.M., Riche, A.B., Dailey, A.G., Gezan, S.A., Powlson, D.S., 2008. Is UK biofuel supply from *Miscanthus* water-limited? Soil Use Manag. 24, 235–245.
Ritchie, P.D.L., Harper, A.B., Smith, G.S., Kahana, R., Kendon, E.J., Lewis, H., Fezzi, C., Halleck-Vega, S., Boulton, C.A., Bateman, I.J., Lenton, T.M., 2019. Large changes in Great Britain's vegetation and agricultural land-use predicted under unmitigated climate change. Environ. Res. Lett. 14, 114012.
Rosch, C., Skarka, J., Raab, K., Stelzer, V., 2009. Energy production from grassland - assessing the sustainability of different process chains under German conditions. Biomass Bioenergy 33, 689–700.
Rytter, R.M., 2012. The potential of willow and poplar plantations as carbon sinks in Sweden. Biomass Bioenergy 36, 86–95.
Schapendonk, A.H.C.M., Stol, W., van Kraalingen, D.W.G., Bouman, B.A.M., 1998. LINGRA, a sink/source model to simulate grassland productivity in Europe. Eur. J. Agron. 9 (2–3), 87–100.
Schneckenberger, K., Kuzyakov, Y., 2007. Carbon sequestration under *Miscanthus* in sandy and loamy soils estimated by natural ^{13}C abundance. J. Plant Nutr. Soil Sci. 170, 538–542.
Scurlock, J.M.O., Hall, D.O., 1998. The global carbon sink: a grassland perspective. Glob. Chang. Biol. 4, 229–233.
Seppala, M., Paavola, T., Lehtomäki, A., Rintala, J., 2009. Biogas production from boreal herbaceous grasses - specific methane yield and methane yield per hectare. Bioresour. Technol. 100 (12), 2952–2958.
Sinclair, T.R., 1986. Water and nitrogen limitations in soybean grain production. Part I. Model development. Field Crops Res. 15, 125–141.
Smith, P., Milne,. R., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K. 2000a. Revised estimates of the carbon mitigation potential of UK agricultural land. Soil Use Manag., 16, 293–295.
Smith, P., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2000b. Meeting the UK's climate change commitments: options for carbon mitigation on agricultural land. Soil Use Manag. 16, 1–11.
Soussana, J.F., Luscher, A., 2007. Temperate grasslands and global atmospheric change: a review. Grass Forage Sci. 62, 127–134.
Stolarski, M.J., Szczukowski, S., Tworkowski, J., Krzyzaniak, M., Załuski, D., 2019. Willow production during 12 consecutive years - The effects of harvest rotation, planting density and cultivar on biomass yield. GCB Bioenergy 11, 635–656.
Styles, D., Jones, M.B., 2007. Energy crops in Ireland: quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass Bioenergy 31, 759–772.
Styles, D., Thorne, F., Jones, M.B., 2008. Energy crops in Ireland: an economic comparison of willow and *Miscanthus* production with conventional farming systems. Biomass Bioenergy 32, 407–421.
Tallis, M.J., Casella, E., Henshall, P.A., Aylott, M.J., Randle, T.J., Morison, J.I.L., Taylor, G., 2013. Development and evaluation of ForestGrowth-SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. GCB Bioenergy 5, 53–66.
Triana, F., Ragaglini, G., Bonari, E., Cerasuolo, M., Richter, G.M., 2011. Modelling the water balance of different grass species used for bioenergy. Biomass and energy crops. Asp. Appl. Biol. 112, 163–170.
Tukey, J.W., 1977. Exploratory Data Analysis, 2. Reading, Mass. (131-160 pp.).
United Nations Framework Convention on Climate Change (UNFCCC), 2015. Adoption of the Paris agreement. In: 21st Conference of the Parties. United Nations, Paris (30 November - 12 December).
Wang, S., Hastings, A., Wang, S., Sunnenburg, G., Tallis, M.J., Casella, E., Taylor, S., Alexander, P., Cisowska, I., Lovett, A., Taylor, G., Firth, S., Moran, D., Morison, J., Smith, P., 2014. The potential for bioenergy crops to contribute to GB heat and electricity demands. GCB Bioenergy 6, 136–141.
Wosten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169–185.
Yang, J., Zhao, H., Zhang, T., 2004. Heat and drought tolerance of two willow species, Salix gordejevii and Salix babylonica: a comparative study. Israel J. Plant Sci. 52, 301–306.
Yang, S., Volk, T.A., Fortier, M.-O.P., 2020. Willow biomass crops are a carbon negative or low-carbon feedstock depending on prior land use and transportation distances to end users. Energies 13, 4251.
Zatta, A., Clifton-Brown, J., Robson, P., Hastings, A., Monti, A., 2014. Land use change from C3 grassland to C4 *Miscanthus*: effects on soil content and estimated mitigation benefit after six years. GCB Bioenergy 6, 360–370.