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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

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Highlights

- Effect of changing climate on biomass production and C sequestration evaluated
- Changing climate helps net primary productivity of perennial bioenergy crops
- Broadleaf willow cultivar *Endurance* is best for C sequestration in this environment
- *Miscanthus* provides greater aboveground biomass for bioenergy
- Land use change can augment non-fossil energy production and C sequestration

Abstract

Reductions in CO_2 emissions are essential to support the UK in achieving its net zero policy objective by 2050. Biomass and bioenergy crops can help deliver net zero by sequestering carbon (C) through capturing atmospheric CO_2. Both changing climate and land use change (LUC) offer an opportunity to deploy suitable bioenergy crops strategically to enhance energy production and C sequestration. 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 assessed if LUC from permanent grassland to perennial bioenergy crops 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 while the broadleaf willow cultivar '*Endurance*' is best suited for C sequestration in this environment, and more so in the changing climate. In the warmer lowlands, LUC from permanent grassland to *Miscanthus* and in the cooler uplands from permanent grassland to '*Endurance*', enhances NPP. The study shows that LUC can help augment non-fossil energy production and increase C sequestration potential in the study environment. In the wake of 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.

Key words: Net zero, Miscanthus, Willow, Climate change, Carbon, Land conversion

1. Introduction

The demand for biomass for energy production is likely to increase in countries that have signed the Kyoto Protocol (1998), 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 (GHG) emissions, including reducing global carbon dioxide (CO_2) emissions by 45% by 2030, relative to the 2010 levels, to reach net zero by 2050 (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 *et al*., 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). 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 GHG emissions without impacting on high quality land (Lovett *et al.,* 2014) with the potential to supply more than 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, ligno-cellulosic crop, would sequester more atmospheric CO_2 by storing it in a long-term reservoir (Agostini *et al.,* 2015).

In England, *Miscanthus* and SRC willow are likely to dominate as PBE crops (Gallardo *et al.,* 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). 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 extant 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.* 2000 a, b). 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 *et al.,* 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).

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 characterised 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.

Given the above context, in this new study, we use process-based models to explore the productivity and C sequestration potential of these land use systems, across a pedo-climatically variable case study catchment. The overall objective was to investigate the effect of changing climate and land use on production and C sequestration potential, to ascertain the best suited PBE crop in both uplands and lowlands in southwest England. More specifically, the objectives of the study were to: i) evaluate the extent of net primary productivity losses/gains for PBE crops, and ii) assess the C sequestration potential of PBE crops in conjunction with land use change from grassland to ligno-cellulosic crops in a wet and warm environment.

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 Hassell *et al.* (2022), we partitioned the study catchment into 44 grid cells each of 1 km ×

1 km (Figure 1). From the headwaters south of the Dartmoor granite plateau, the elevation drops from ~550 to 145 m above sea level.

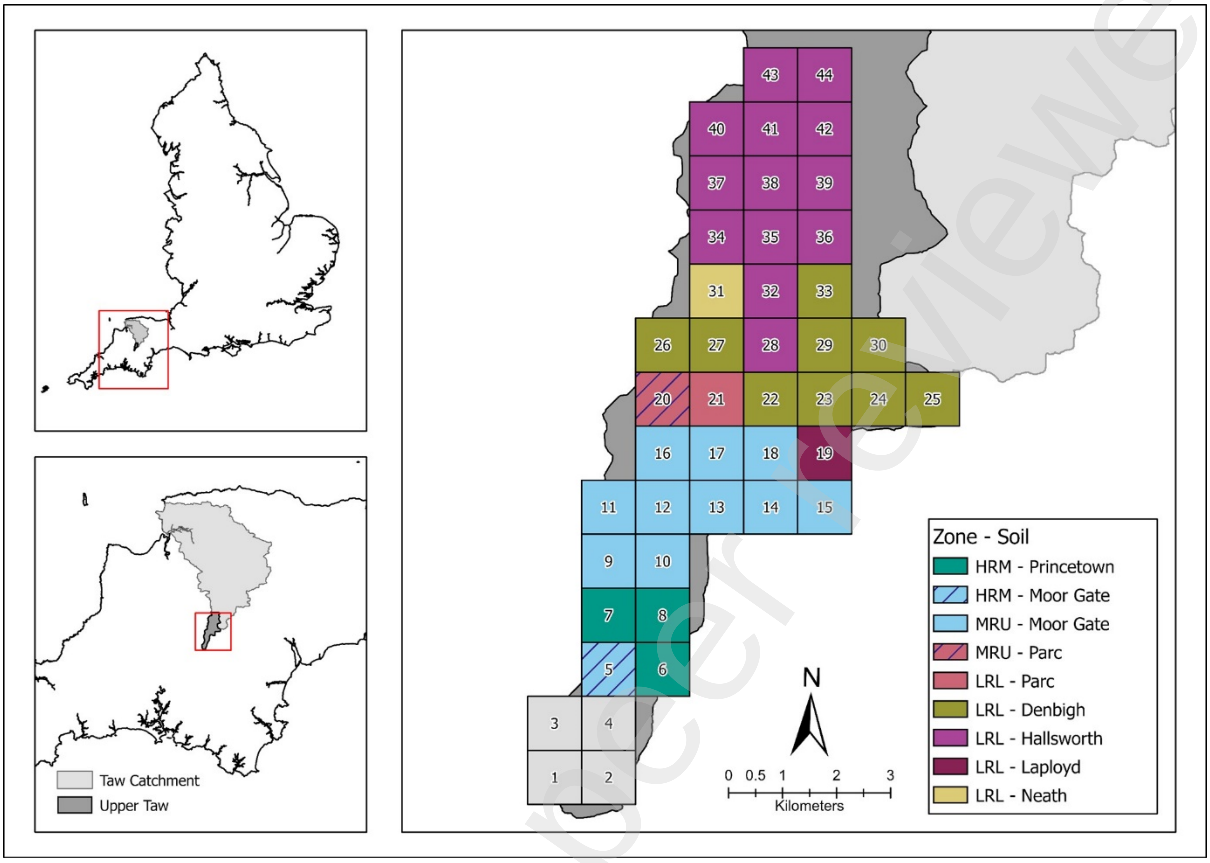

Figure 1. The location of the 44 km^2 study site in the upper River Taw catchment in southwest England. Different zones of weather and soil names are shown and each cell covers an area of 1 km x 1 km. The different weather zones are the high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL).

The study area is characterized by three weather zones and seven soil types (Figure 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 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 1) 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 while 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. While 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).

Table 1 Mean monthly and annual precipitation and air temperatures for baseline (1981-2000) and recent (2001-2019) climate in the high rainfall moorland (HRM), medium rainfall upland (MRU) and low rainfall lowland (LRL) zones. Atmospheric CO_2 concentration is 355 ppm and 390 ppm for these climates, respectively.

	Mean monthly and annual precipitation (mm)						**Mean monthly and annual air temperature (°C)**					
	HRM		**MRU**		**LRL**		**HRM**		**MRU**		**LRL**	
Year	***Baseline***	***Recent***	***Baseline***	***Recent***	***Baseline***	***Recent***	***Baseline***	***Recent***	***Baseline***	***Recent***	***Baseline***	***Recent***
Jan	263.9	241.7	197.3	180.7	144.4	132.3	3.03	3.39	3.33	3.72	3.90	4.36
Feb	187.2	186.5	139.9	139.4	102.4	102.0	2.90	3.17	3.18	3.48	3.73	4.07
Mar	180.1	172.9	134.6	129.2	98.5	94.6	4.06	4.10	4.46	4.51	5.23	5.28
Apr	150.3	121.7	112.4	91.0	82.3	66.6	4.83	5.47	5.31	6.01	6.21	7.03
May	142.4	141.8	106.5	106.0	77.9	77.6	6.78	7.13	7.45	7.83	8.72	9.17
Jun	115.1	124.1	86.0	92.7	63.0	67.9	8.42	9.00	9.25	9.89	10.84	11.58
Jul	100.9	139.7	75.4	104.4	55.2	76.4	9.87	10.00	10.85	10.99	12.71	12.87
Aug	135.0	136.9	100.9	102.3	73.9	74.9	9.83	9.87	10.80	10.84	12.65	12.69
Sep	184.9	125.4	138.2	93.8	101.2	68.6	8.46	8.74	9.29	9.61	10.88	11.25
Oct	245.4	225.3	183.4	168.4	134.3	123.3	6.53	7.14	7.18	7.85	8.41	9.19
Nov	249.1	237.8	186.2	177.8	136.3	130.1	4.69	5.10	5.15	5.60	6.04	6.56
Dec	301.7	245.3	225.5	183.4	165.1	134.2	3.55	3.77	3.90	4.14	4.56	4.84
Annual	**2256**	**2099**	**1686**	**1569**	**1234**	**1148**	**6.10**	**6.42**	**6.70**	**7.06**	**7.84**	**8.26**

While 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. While the annual precipitation decreased under recent climate, it did not decrease in the summer months from June to August (Figure S1). 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 1, Figure S1).

2.2.2 Soils data

Soil information was available in the form of texture analysis, organic matter and bulk density from the fundamental soil property tables provided in the NATMAP database (Hallett *et al*., 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 plant available water capacity (PAWC), water retained between field capacity and permanent wilting point (-33 kPa and -1500 kPa suction pressure, respectively of a given soil), was computed for each soil layer. The soils varied from sandy to clayey, with the PAWC 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 S1). 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 Modelling package description

We used AGREMOSA (AGRicultural Environment MOdelling and Systems Analysis), a modelling and optimization framework of process-based models simulating water-limited production of arable and 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 is based on the STAMINA modelling framework (Richter *et al.*, 2006) which covers a wide range of arable crops, following the principles of SUCROS (van Laar *et al.*, 1997) and was successively expanded implementing 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).

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) and 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 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 above ground (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 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.

2.4 Simulation scenarios and long-term simulations

LINGRA and LUCASS, as implemented in AGREMOSA, were used to simulate the two land uses: i) improved permanent grassland (IPG), and ii) the two 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 (BL, leaf width 20–27 mm) closed-canopy cultivar and '*Tora'* (*S. schwerinii* × *(S. viminalis* × *viminalis)*), a narrow-leaf (NL, 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).

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), while 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). Both *Miscanthus* and willows simulations were performed assuming non-N-limited growth; in practice 50 kg N ha^{-1} are applied after harvest.

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 (Figure 1, Table S1). 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. Detailed soil information is given in Table S1. The first two years (1981 and 1982) and the last year (2019) of the simulation results were removed from analysis, leaving 36 years of simulation (*i.e.*, 18 years for each climate scenario) for analysis.

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 and 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. In addition, 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 and belowground biomass

3.1.1 Improved Permanent Grassland (IPG)

3.1.1.1 NPP of 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 (Figures 2, 3). 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 2). These results corroborate with 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 (GB). For moorland and upland, we also simulated changes for rough grazing production and found that the average increase in NPP was only 0.08 t ha^{-1} due to changing climate (4.38 in the baseline and 4.46 t ha^{-1} for recent climate).

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. While grid cells 20 and 21 have the same soil properties, they fall in different weather zones, and 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.

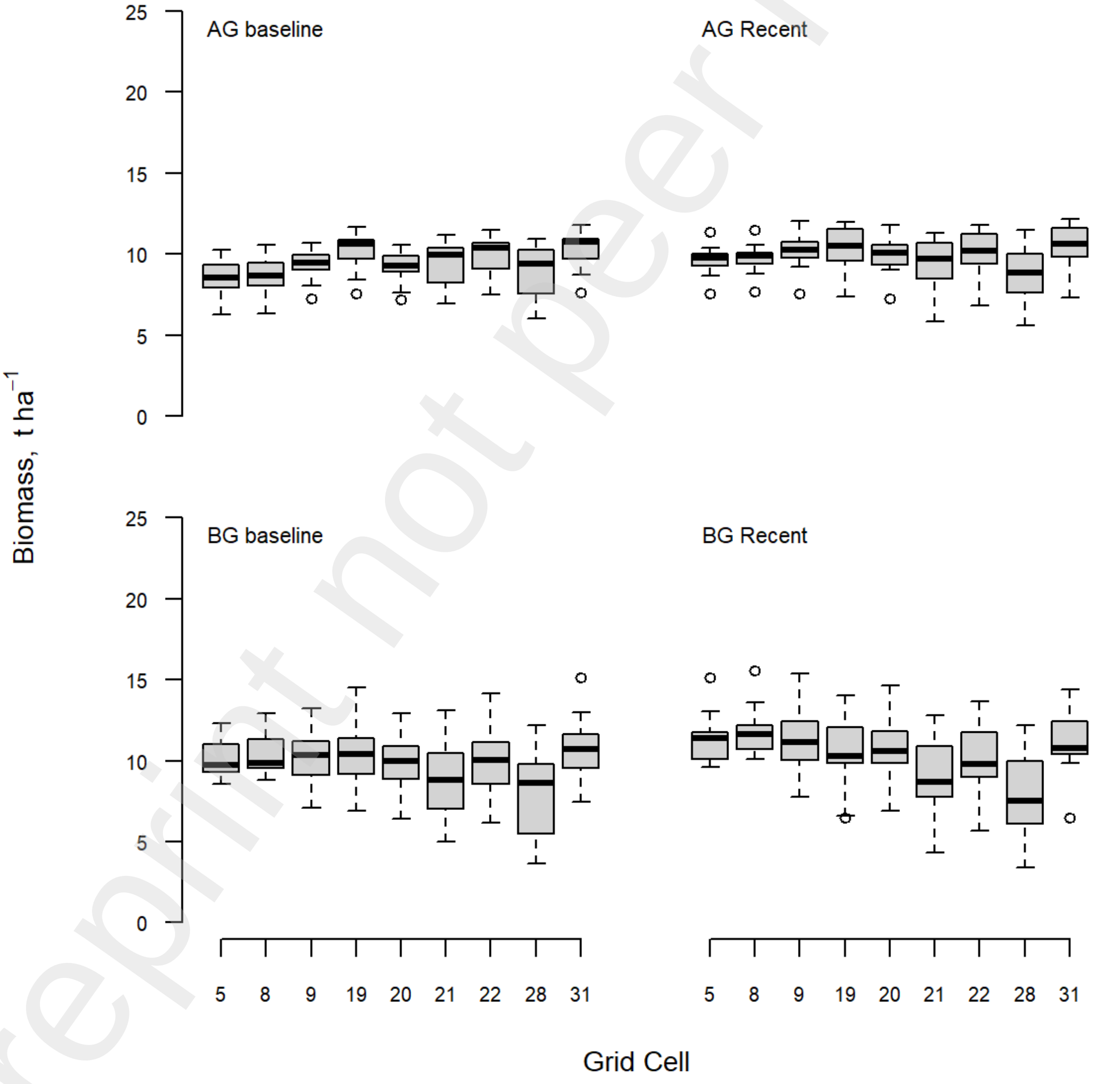

Figure 2. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for improved permanent grassland (IPG) in different grid cells during baseline and recent climate.

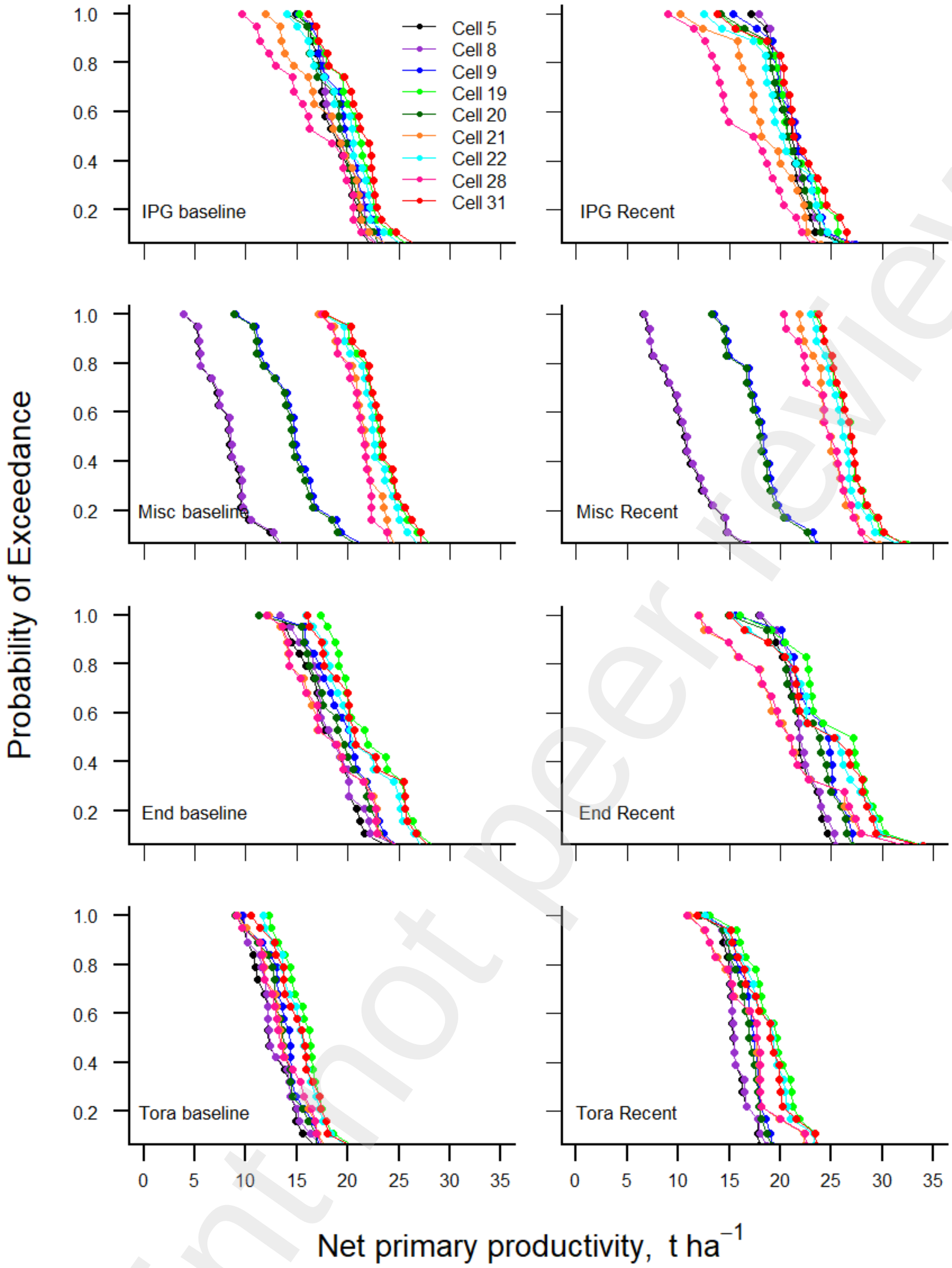

Figure 3. Probability of exceedance of net primary productivity (NPP) (t ha^{-1}) of different land uses in different grid cells during baseline and recent climate. The different land uses are: improved permanent grassland (IPG), *Miscanthus* (Misc) and the '*Endurance*' (End) and '*Tora*' cultivars of willow.

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The upper 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 2). 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).

Table 2 Mean percentage change in net primary productivity (NPP) of different PBE crops from baseline to recent climate.

	Mean change in NPP (%)			
Grid Cell	***IPG***	***Miscanthus***	***Willow***	
			Endurance	*Tora*
5	12.0	31.4	20.5	23.3
8	11.7	30.7	19.2	22.0
9	8.8	22.7	19.3	22.6
19	3.1	15.8	14.0	20.9
20	8.7	23.3	19.3	22.9
21	2.0	16.5	14.8	23.1
22	2.8	16.1	14.4	21.5
28	-0.9	16.2	15.3	24.1
31	3.1	15.6	12.7	21.4
Average	**5.8**	**18.9**	**16.5**	**22.4**

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 (Tukey's honest significant difference (HSD) *posthoc* test at $p<0.5$; see Table S2). The changes in NPP for corresponding cells were also not statistically significant. Only grid cells 28 and 31 had significantly different NPP for the baseline scenario, while cell 28 had significantly different NPP from cells 5, 8, 9, 19, 20 and 31 for the recent climate scenario (Table S3). This suggests that weather, soil and their combination determine the overall impacts; however, the effect of weather appears to be greater in the case of biomass production.

3.1.1.2 Partitioning of 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 (Figure 2). 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 3), having favourable implications for improving SOC.

Table 3 Mean percentage change in aboveground (AGB) and belowground biomass (BGB) of different PBE for baseline and recent climate.

	Mean change in AGB (%)				**Mean change in BGB (%)**			
Grid Cell	***IPG***	***Miscanthus***	***Willow***		***IPG***	***Miscanthus***	***Willow***	
			Endurance	*Tora*			*Endurance*	*Tora*
5	11.5	53.2	59.9	51.2	12.5	14.3	8.9	11.3
8	11.4	52.0	56.4	48.7	12.0	13.9	7.9	10.4
9	7.8	37.1	40.1	40.0	9.7	7.7	6.2	7.1
19	2.6	23.3	18.6	21.3	3.6	6.0	8.3	20.0
20	7.6	38.0	40.1	40.4	9.8	8.1	6.3	7.4
21	1.3	25.0	19.3	23.4	2.9	5.5	9.5	22.6
22	2.3	23.8	18.9	21.9	3.4	5.9	9.0	20.7
28	-1.9	24.7	19.9	24.3	0.1	5.2	10.1	23.9
31	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**

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 (Figures 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 S2). In the case of disaggregated grid cells, only the differences between grid cells 8 and 28 were statistically significant for BGB under recent climate (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.

3.1.2 Miscanthus

3.1.2.1 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 more than 30% and 22% in the moorland and upland zones, respectively. For the lowlands, NPP increased in the range of 15.5 to 16.5 %. Over all simulated cells, the net increase in NPP was ~19% (Table 2). 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, while 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 S2). Moorland and upland had significantly lower NPP than the warmer lowland cells for both baseline and recent climate (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 (Figures 3, 4), which eliminates the steep, high rainfall slopes from growing *Miscanthus* for economic reasons as well as challenges associated with harvesting. Looking at the probability of exceedance of NPP for *Miscanthus* (Figure 3) it is clear that temperature acts as an important control in the study environment, where precipitation is not limiting (Heaton *et al*., 2004).

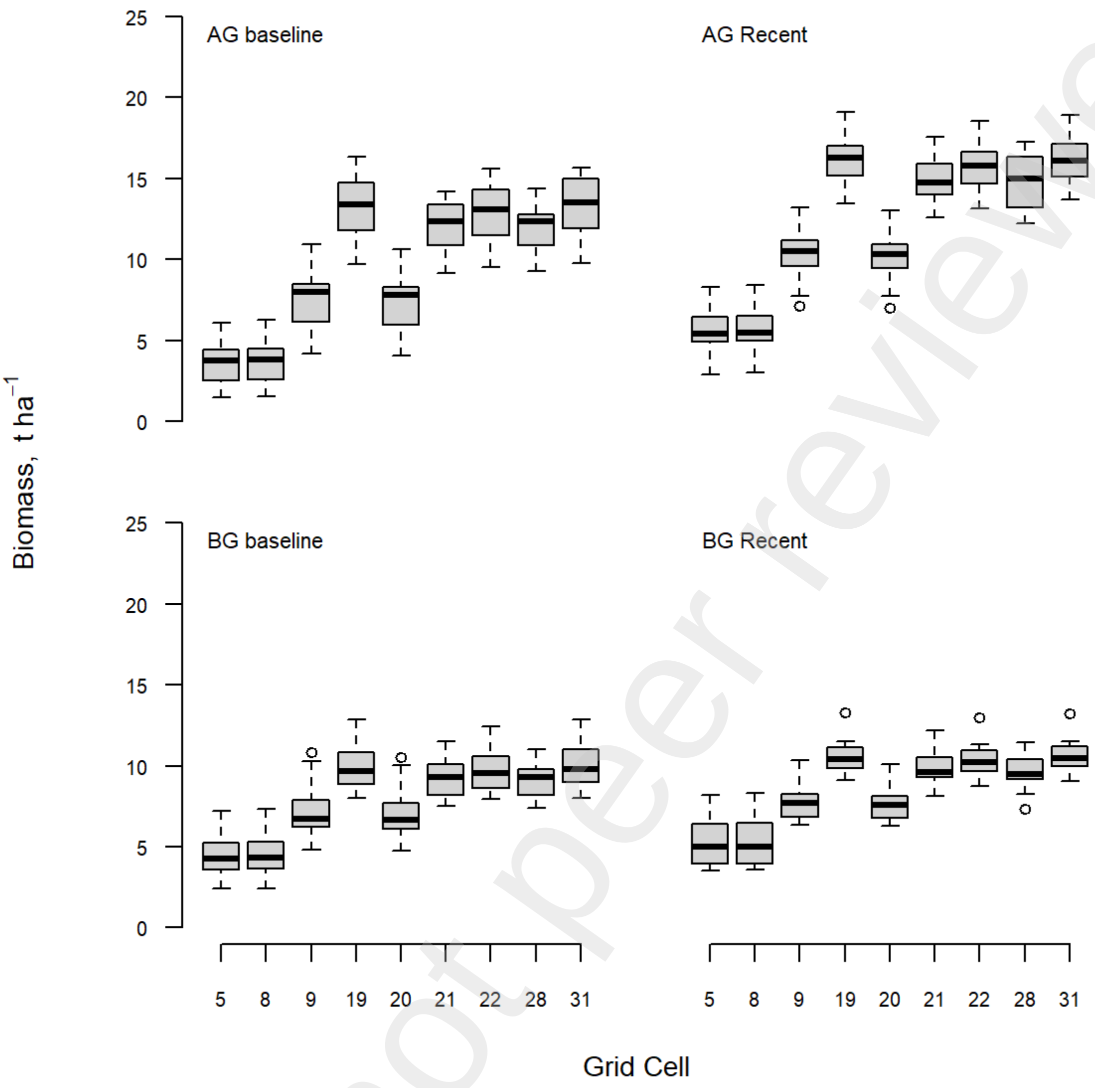

Figure 4. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for *Miscanthus* in different grid cells during baseline and recent climate.

3.1.2.2 *Partitioning of 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 3, Table S2). 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 (Figure 4). 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 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) while Richter *et al*. (2008) estimated an overall national average *Miscanthus* yield of 9.6 t ha^{-1} with a corresponding range of 5 to 18 t ha^{-1} (average of 12.8 t ha^{-1}) over 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) (Figures 2, 4). 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 3). 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, while warmer cells remain more resilient and consistent (Figures S2, S3). Thus, while overall greater benefits will be achieved due to changing climate, the uncertainty will also be higher in the cooler zones of the study area.

3.1.3 SRC-Willow

3.1.3.1 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 2). 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'*. While the absolute NPP is higher for '*Endurance*', the trends of increase due to changing climate are greater in the case of *'Tora'* (Figures 5, 6). 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 (Figure 3). 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 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 S2).

3.1.3.2 Partitioning of 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 (Figures 5, 6). 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 from *'Tora'*.

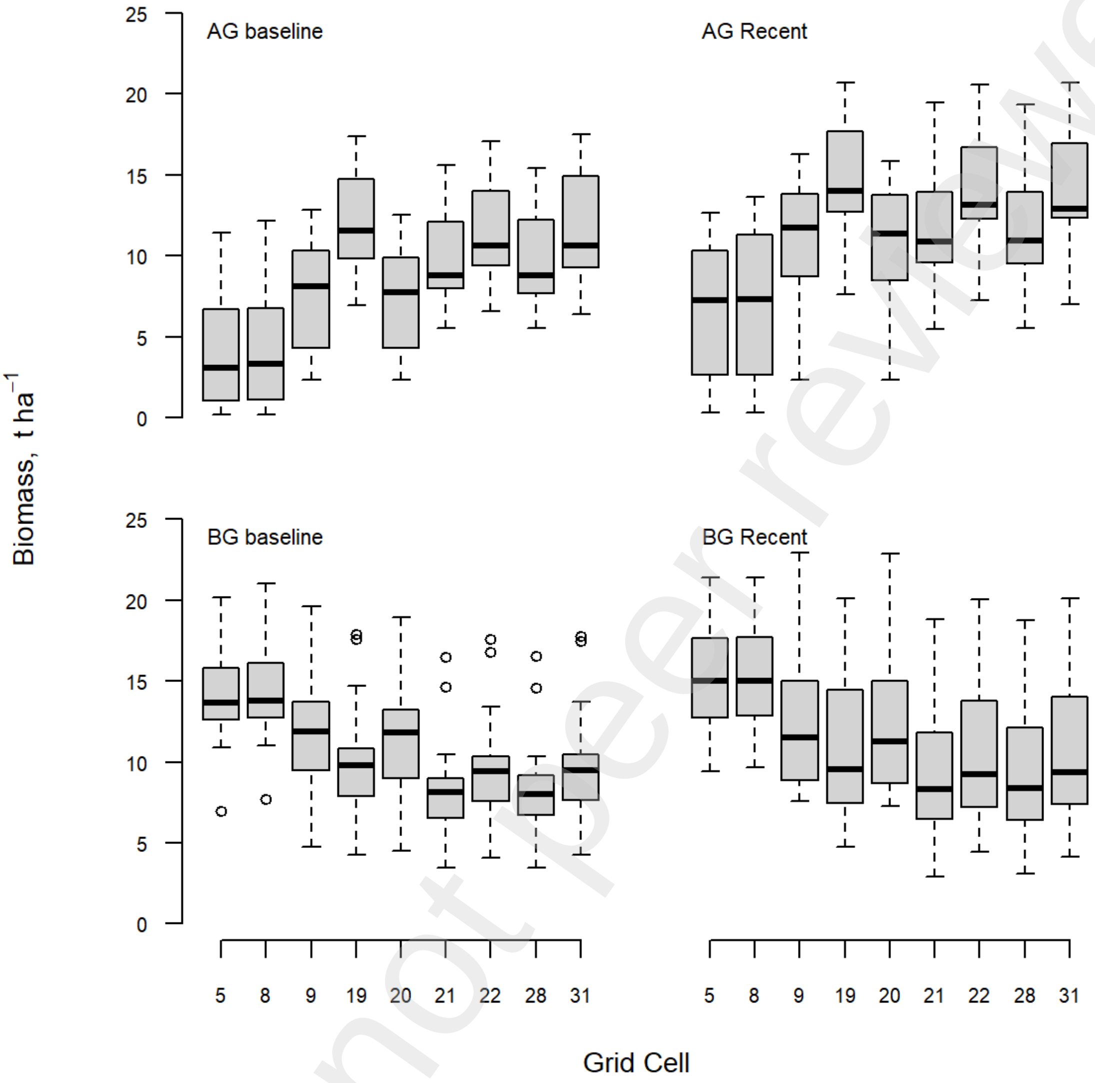

Figure 5. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for the broad-leaf willow cultivar '*Endurance'* in different grid cells during baseline and recent climate.

These results compare well with existing literature. Tallis *et al*. (2013) reported an annual willow yield of 9.0 t ha^{-1} while 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.

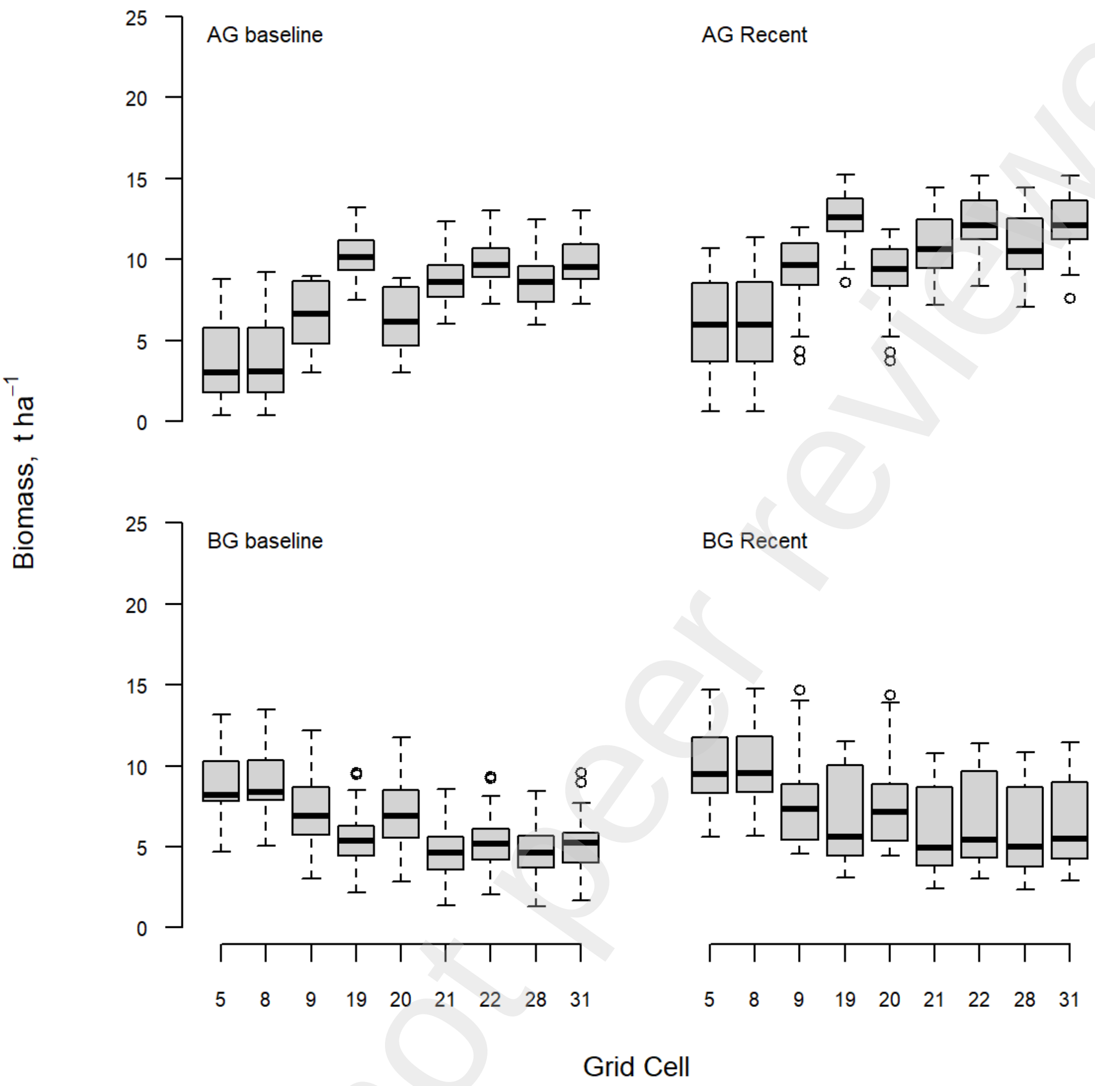

Figure 6. Aboveground (AG) and belowground (BG) biomass production (t ha^{-1}) for the narrow-leaf willow cultivar '*Tora'* in different grid cells during baseline and recent climate.

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 3). 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 HRM and MRU zones (Table 3). 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.

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 S2). 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 Figures 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.

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 4). '*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 4).

Table 4 Mean percentage change in the net primary productivity (NPP) of *Miscanthus* and willow considering improved permanent grassland (IPG) as the baseline land use.

	Mean change in NPP (%)					
Grid Cell	***Miscanthus***		***Willow***			
			Endurance		*Tora*	
	Baseline	Recent	Baseline	Recent	Baseline	Recent
5	-56.7	-49.2	-3.1	4.2	-32.3	-25.5

8	-57.0	-49.7	-3.2	3.3	-32.7	-26.4
9	-24.9	-15.3	-0.3	9.4	-29.5	-20.6
19	12.9	26.9	8.3	19.8	-22.7	-9.4
20	-24.1	-13.9	-0.2	9.4	-29.0	-19.8
21	18.3	35.0	0.7	13.4	-24.6	-9.0
22	14.8	29.5	7.7	19.9	-22.2	-8.0
28	26.0	47.8	8.8	26.7	-18.9	1.6
31	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

Miscanthus performed better in the warmer zone under baseline 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, while 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 5), there is always a decrease of AGB in moorland for *Miscanthus* under both baseline and recent climate and slight increase of ~2 % in the cooler uplands under recent climate.

Table 5 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.

	Mean change in AGB (%)						**Mean change in BGB (%)**					
Grid Cell	*Miscanthus*		*Willow*				*Miscanthus*		*Willow*			
			Endurance		Tora				Endurance		Tora	
	Baseline	Recent	Baseline	Recent	Baseline	Recent	Baseline	Recent	Baseline	Recent	Baseline	Recent
5	-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	-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	-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	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	-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	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	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	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	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

‘*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 *et al*., 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, while 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 land use change 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 SRC willow (Jug *et al*., 1999; Makeschin, 1994). Thus, the existing literature clearly provides conflicting results regarding the organic C stored in the soil when land use is changed from grassland to *Miscanthus* although less so for willow. 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 land use change 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 BGB affect SOC differently which is controlled by the decay rate of plant material on the surface (dead leaves and litter) and the root growth below the surface including 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% (Figure 7) considering all the zones in the study area.

For *Miscanthus*, the changes in 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 %. While the amount of roots decreased by 8% and rhizome by 5%, the dead leaves increased by 11.7% (Figure 7). Dead leaves and litter input to the soil plays an important role in sequestering C in a mature crop (Lewandowski *et al*., 2000; Clifton-Brown *et al*., 2004) and while 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 less than 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% (Figure 7). 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 changes.

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 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).

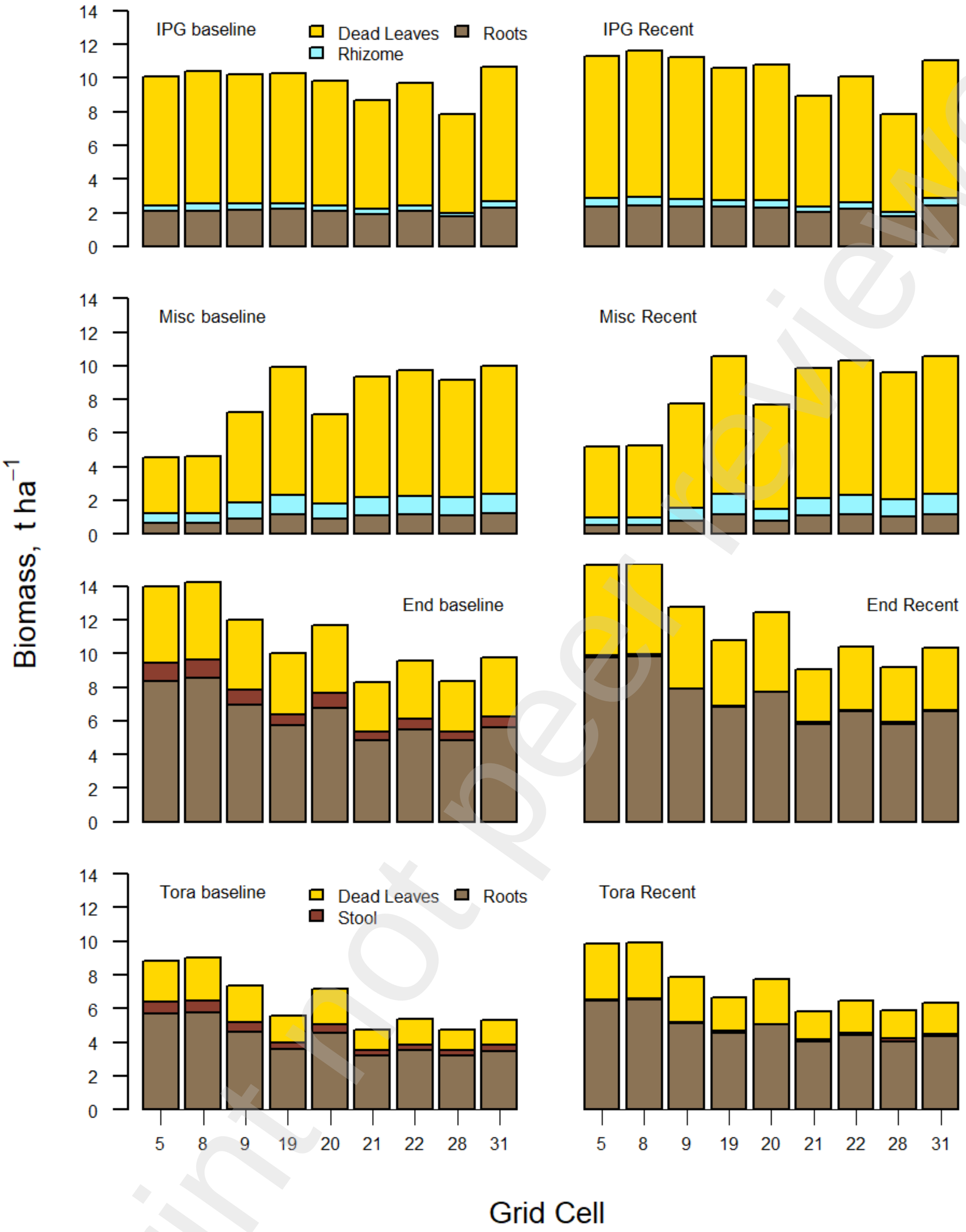

Figure 7. Belowground biomass components (t ha^{-1}) of different land uses in different grid cells during baseline and recent climate. The different land uses are: Improved permanent grassland (IPG), *Miscanthus* (Misc) and the '*Endurance*' (End) and '*Tora*' cultivars of willow.

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.

In a comprehensive review, 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 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.

Figure 7 shows that the major changes in belowground components, along with the total BGB (Table 5), are only predicted for the willow cultivar '*Endurance*' when we shift the land use from IPG. While 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

Changing climate is predicted to positively impact the harvestable productivity and litter plus belowground biomass input of all perennial bioenergy crops in the upper River Taw catchment, southwest England. 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 perennial bioenergy crop and targeted deployment in specific climatic zones. For the entire study area, *Miscanthus* is best suited in terms of bioenergy production while the broadleaf willow cultivar '*Endurance*' is best suited for C sequestration 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 while, in the cooler upland and moorland zones, '*Endurance*' is the best LUC for enhancing NPP. 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 energy production and C sequestration potential in geographies with similar environment conditions to the study area.

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