

The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates

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Abstract

Process and empirical-based models that describe lignocellulosic biomass yield of the perennial energy grass *Miscanthus* (MiscanFor©), short rotation coppice (SRC) trees and shrubs, poplar and willow (ForestGrowth-SRC) and a number of short rotation forest trees (ESC-CARBINE), were used to estimate the yield potential for current and future climates across Great Britain (GB). In current climates, modelled yields for all feedstock crops varied between 8.1 and 10.6 Mg dry weight (DW) ha⁻¹ yr⁻¹ with willow SRC and poplar SRF producing the lowest and highest yields respectively. For the medium emissions scenario (UKCP09) in 2050, mean yield for all feedstock crops varied between 7.6 and 12.7 Mg DW ha⁻¹ yr⁻¹ with willow SRC and poplar SRF once again the lowest and the highest recorded yields. There were clear geographical trends within GB. *Miscanthus* yield was higher than all others in the south-west (13.1 Mg DW ha⁻¹ yr⁻¹), SRC willow and SRC poplar in the north-west (12.1–15.8 Mg DW ha⁻¹ yr⁻¹) and in the midlands and south-east, SRF poplar was the highest yielding (10.5–11.6 Mg DW ha⁻¹ yr⁻¹). These geographical trends changed little with climate out to 2050, with mean yield of each ‘best feedstock’ increasing from 12.7 to 14.2 Mg DW ha⁻¹ yr⁻¹. Out to 2050, SRC declined slightly and *Miscanthus* and SRF poplar increased as the ‘best feedstock’ option. Except for a few localized examples, only SRF poplar had a higher yield than SRC or *Miscanthus*. These data suggest that in current and future climates, lignocellulosic biomass plantation species can be selected and optimized for best yield performance in different regions of GB. This modelling framework provides a valuable starting-point for which to test the performance of new genetic material, as this becomes available and parameterized for the models and socio-economic scenarios that may impact on the bioenergy industry.

Introduction

Climate change and the predicted rise in global population are placing natural resources under extreme pressure by increasing global demand for food, water and energy (Godfray et al., 2010). It is estimated that over the next few decades global demand for energy could increase by 35% when compared to current day supply, with fossil fuels accounting for 74% of the total (IEA, 2010). Rapid decarbonization of current and future energy supplies is critical to stabilize the climate (Le Quéré et al., 2009) and bioenergy is an important part of the renewables mix to tackle this pressing issue. Bioenergy currently provides 10% of global primary energy, mainly in Africa and Asia (Sims et al., 2006), but analysis suggests that up to 20% of global energy demand could be met by biomass without impact on food supply (IEA, 2009; Beringer et al., 2011; Slade et al., 2011). In the United Kingdom, about 3% of primary energy was from renewables over the last few years (2010–2012), with bioenergy contributing ca. 60% of this supply (DECC, 2012a). However, much of the current biomass feedstock for bioenergy is imported and this is expected to continue up to 2050 (Howes et al., 2011; DECC, 2012b). The sustainability of bioenergy has been questioned, since this depends on end use, feedstock crop type, land use conversion and proximity to end users. In some cases, bioenergy crops may have a poor greenhouse gas balance (GHG), relative to fossil fuel alternatives, for example, palm oil from native rainforest (Fargione et al., 2008) and may also compete directly with land for food production, contributing to increased food prices (Mittal, 2009). Alternatively, bioenergy can be sustainable, enhancing a number of ecosystem processes and services and offering a large GHG saving compared to the fossil fuel alternative, for example, locally grown lignocellulosic crops converted from annual arable cropping (Hillier et al., 2009; Rowe et al., 2009, 2013; Whitaker et al., 2010) with the potential for carbon negative fuels through carbon capture and sequestration (Gough & Upham, 2009).

Within Europe, future scenarios suggest that 44–53 Mha of cultivated land could be used for bioenergy feedstock production by 2030 (i.e. more than a 1000% increase of land for this use) (Fischer et al., 2010; Don et al., 2011). The UK Government estimates that bioenergy could account for 10–12% of primary energy by 2050 (DECC, 2012b) with limited impact on food supply. The theoretical maximum available land for dedicated lignocellulose crops/plantations has been estimated to be between 0.9 and 3.6 Mha in England and Wales (i.e. between 6% and 24% of the total land area of England and Wales). The United Kingdom has mandated in law that it will reduce greenhouse gas emissions by 80% by 2050 (UK Climate Change Act,

2008) and it is likely that the use of bioenergy will contribute to this, at least in part, using dedicated 'second generation' (2G) lignocellulosic crops/plantations, that is, including Short Rotation coppice (SRC), Miscanthus and short rotation forestry (SRF) (Somerville et al., 2010; McKay, 2011; DECC, 2012b; Valentine et al., 2012). These perennial crops require lower inputs (e.g. fertilizers, herbicides, pesticides, irrigation) and can grow on marginal land, so not directly competing with food and feed, and offer the larger offsets of GHG compared to fossil fuel alternatives (Hastings et al., 2009a,b; Hillier et al., 2009; Tilman et al., 2009). Between 2010 and 2011, an estimated 10 Kha of land in England made up by 78% Miscanthus and 22% SRC willow was planted under the energy crop schemes (ECS) (ES1 and ES2 – planted between 2000 and 2012). From this, only 45 000 Mg of biomass has been supplied to biomass power stations under the renewable obligations scheme (Aylott & McDermott, 2012). This domestic second generation biomass supply is estimated to provide the equivalent of 0.2 TWh if converted to electricity (DECC, 2012b), giving an estimated 0.4% offset of the total UK energy usage (203 million tonnes of oil equivalent in 2011) (DECC, 2012c).

To meet UK targets, a substantial increase in the rate of energy crop planting is required in the very near term and there is thus an urgent need to predict the most suitable locations for feedstock types that are ecologically and economically sustainable in Great Britain GB, in both current and future climate conditions. Recent SRC yield modelling and mapping exercises suggested that 7.5 million Mg of biomass are available from 0.8 Mha of land not impacting food production in England, this could provide about 4% of current UK electricity demand with a mean yield of $9.7 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (Aylott et al., 2008, 2010). However, the empirical yield model used in this study was unable to predict SRC growth under future climates. Similarly, empirical modelling of Miscanthus yields gave a mean of 12.5 Mg ha^{-1} for England when grown on more productive land (Richter et al., 2008; Lovett et al., 2009). Short-rotation forestry (SRF), which is the practice of cultivating fast-growing trees with a planting density of about 2500 trees per hectare that reach their economically optimum size between 8 and 20 years old, may also have the potential to deliver greater volumes of biomass from the same land area than alternative biomass crops (McKay, 2011). These trees are generally grown on lower grade agricultural land, previously forested land or reclaimed land and so do not directly compete with food crops. However, experience of SRF in the United Kingdom is limited, creating a need to establish whether it is a viable renewable energy source.

In this article, a modelling framework was developed to map at a 1 km² grid-resolution the expected yields of Miscanthus (*Miscanthus* × *giganteus*), SRC willow genotype Joruu (*Salix viminalis* L. × *S. viminalis*), SRC poplar genotype Trichobel (*Populus trichocarpa* Torr. & A. Gray × *P. trichocarpa*) and for the first time SRF for poplar (mixed cultivars: *trichocarpa*, *deltoids*, *nigra* (TDN) and Aspen, *Populus tremula* L.), black alder (*Alnus glutinosa* L.), European ash (*Fraxinus excelsior* L.), Sitka spruce (*Picea sitchensis* [Bong.] Carr.) and silver birch (*Betula pendula* Roth) for the whole GB, now and out to 2050 when accounting for the UKCP09 (Murphy et al., 2009) climate change scenarios. Within this framework, yields were generated using the MiscanFor© (Hastings et al., 2009a), ForestGrowth-SRC (Tallis et al., 2013) and ESC-CARBINE (Thompson & Matthews, 1989; Pyatt et al., 2001) UK-dedicated feedstock-specific models for which simulations of plant growth and yields have been well validated from GB field trials.

Materials and methods

The yield of each feedstock was calculated for each 1 km² grid within GB with its respective dedicated biomass plantation type model using the same soil and meteorological data. Note that plant responses to irrigation, mineral fertilization, pests and disease and genetic and/or agronomic improvements were not considered in this study. Constraint maps from Sunnenberg et al. (2013) were used to define which grid blocks could be used for feedstock production and the best feedstock for each grid block determined so that the energy yield could be determined under current and future conditions.

Yield models

The MiscanFor© model

For Miscanthus yield modelling the MiscanFor© process-based model described in Hastings et al. (2009a,b) was used. MiscanFor© was developed from the MISCANMOD model (Clifton-Brown et al., 2000) and successfully tested against yield observations ($R^2 = 0.84$) from across the United Kingdom (UK) and Europe (Hastings et al., 2009a). MiscanFor© was used to estimate energy yield from Miscanthus for current condition and future climate scenarios (Hastings et al., 2009b) for the EU 27 countries at a coarse scale (5° grid) and predicted that 10% of arable land could produce a net biomass energy yield of 89.9 PJ yr⁻¹ in the United Kingdom, with a mean yields of between 10 and 12 Mg ha⁻¹. MiscanFor© is parameterized for

several giant grass species but for this study was used to model the highest yielding commercially grown variety; *Miscanthus × giganteus*. The model requires the soil parameters of field capacity and wilting point to calculate the soil moisture deficit from the balance between actual evapo-transpiration and rainfall and soil organic carbon to estimate the change in soil carbon. The plant growth module is driven by air temperature and incident photosynthetically active radiation. Changes in atmosphere carbon dioxide concentration [CO_2] were not considered in this study for C4 grasses as the impact of increasing [CO_2] on yield has been shown to be minimal in many C4 plant species (e.g. Leakey, 2009) and no published experiments exist for *Miscanthus*.

The ForestGrowth-SRC model

For SRC willow and poplar, the ForestGrowth-SRC process-based model described in Tallis et al. (2013) was used to model yields. ForestGrowth-SRC was developed from a forestry growth model 'ForestGrowth' (Evans et al., 2005a) that proved successful in simulating gross primary production, potential evapotranspiration (ETp) and timber yield for a number of forest ecosystems across Europe (Evans et al., 2005a, b). Yields modelled by ForestGrowth-SRC compared well ($R^2 = 0.85$) with 6 years of measured annual growth for seven diverse SRC poplar and willow sites across the United Kingdom (Tallis et al., 2013). For a further 25 monoclonal SRC sites (Armstrong, 1997; Aylott et al., 2008), both measured and modelled yields of willow gave a mean of $8.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for two rotations and the mean modelled yields for the whole United Kingdom (not including carbon rich soils $\geq 30\%$ SOC) was $9.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (Tallis et al., 2013) and this equalled the mean measured yield from all 49 growth trial sites across the United Kingdom (Aylott et al., 2008). The development and evaluation of ForestGrowth-SRC for both SRC willow genotype Joruun and SRC poplar genotype Trichobel are reported in Tallis et al. (2013) and Joruun and Trichobel were accepted as the best willow and poplar genotypes, respectively, with which to evaluate the model and were used in this study. ForestGrowth-SRC has the ability to model new genotypes as parameter values become available. For each decade management was set on a 3 years harvest cycle following the coppice of a single establishment year (DEFRA, 2004), and the mean yield from the three harvests was calculated. The atmosphere carbon dioxide concentration was set to $380 \mu\text{mol mol}^{-1}$ (Tans & Keeling, 2012) for the 2010 decade (the 2000–2010 mean) and as reported for the BERN-CC model (Prentice et al., 2001)

for climate change scenarios. Yields simulated by ForestGrowth-SRC respond to increasing [CO₂] as predicted from experimental work (Tallis et al., 2013).

The ESC-CARBINE model for SRF

A model for SRF yields was developed as a combined empirical model encompassing both the Ecological Site Classification (ESC) decision support tool developed by Pyatt et al. (2001) and the CARBINE model developed by Thompson & Matthews (1989) to predict the likely impacts of environmental changes on SRF yield. Maximum mean annual increment in timber volume (yield class, m³ ha⁻¹ yr⁻¹) distribution maps for the selected tree species was generated from the knowledge of forest scientists as well as tree species suitability modelling using the decision-support tool ecological site classification (ESC) developed by Pyatt et al. (2001). ESC focuses on a multidimensional approach to site classification, assessing four climate (warmth, wetness, continentality and windiness) and two soil (moisture and nutrient regimes) factors, and three species suitability classes (very suitable, suitable and unsuitable) to the particular climates and soil types. For each species, the range of values of each climatic factor is divided into three sectors and labelled with these ratings (Fig. 1). The classes of soil moisture regime and soil nutrient regime are rated in a similar way (Fig. 1). When combining the ratings of each factor to reach an overall suitability for a given site, it is the lowest rating that will determine the outcome. In very suitable conditions, a species is expected to grow at a rate given by the upper third of the range of yield class shown in the Yield Models for Forest Management (Edwards & Christie, 1981). In suitable conditions, unless limited by cold temperatures, a species is either expected to grow at a rate given by the middle third of the range of yield class in the Yield Models, or expected to grow well early in its life, but with reduce growth in the later part of the rotation. A species is considered unsuitable when the one of the factors falls into the unsuitable zone (Fig. 1). It is assumed that climatic and soil factors cannot compensate for one another. Thus, a very suitable climate cannot compensate in terms of yield for an unsuitable soil quality, and vice versa. Similarly, if any one factor (climatic or soil) is unsuitable, a favourable rating of any other factor cannot make the species suitable for the site. The species suitability criteria are essentially subjective, but draw on forestry experience in the United Kingdom and abroad. Predictions in yield class by the ESC tool are as following: for a given site the climatic values are computed and the classes of soil moisture and nutrient regime are estimated. Each value is marked on the horizontal axes and values of potential yield class and ratios are read off. Whichever is the

lowest ratio, it is then multiplied by the potential yield class value to obtain the predicted yield class. The above-ground potential yields (dry Mg ha⁻¹) distribution maps were then generated from the ESC model outputs by the CARBINE model developed by Thompson & Matthews (1989). The CARBINE model includes a set of yield class-dependent timber volume production curves/data (m³ ha⁻¹) for a set of tree species (Edwards & Christie, 1981). The CARBINE model works at an annual time step. To model volume estimates for SRF, all outputs were based on a rotation of 20 years. The estimates of timber volume were then converted into estimates of dry matter by multiplying the stem volume by the basic density/nominal-specific gravity of each species. Accumulated dry matter in the branch and coarse root components were estimated by assuming simple allometric relationships with timber masses (Thompson & Matthews, 1989). Note that plant responses to [CO₂] increases in the atmosphere were not accounted for by this approach as there is not yet any data from field experiments to parameterize this effect for all the species considered.

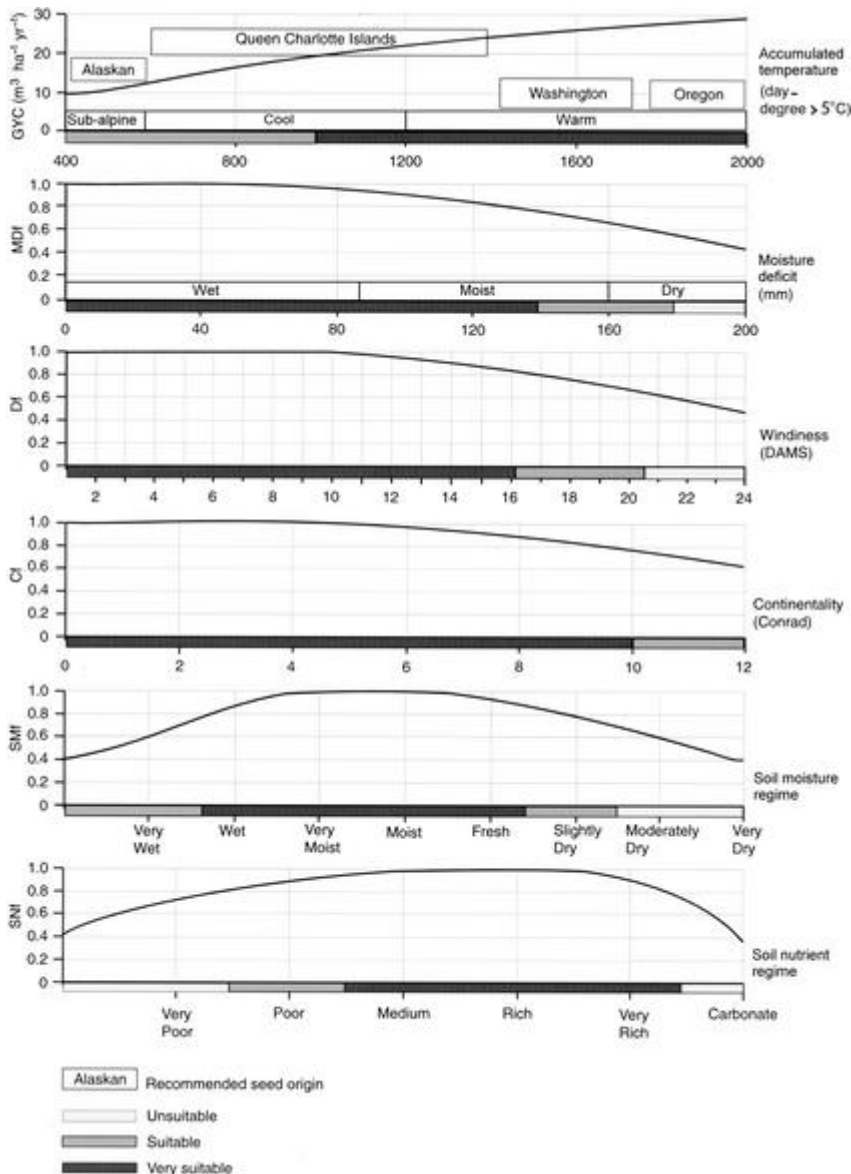


Figure 1 Example of smooth response curves for Sitka spruce used during the ecological site classification procedure. The uppermost curve shows how yield class is assumed to be related to accumulated temperature, given that other climatic and soil conditions are ideal for the species. The remaining curves show how the potential yield class of the species is held to be affected by variation in the other climatic and soil factors (adapted from Pyatt et al., 2001).

Climate data

The climate data used to drive all three models were the UKCP09 data set prepared by the UK Met Office Hadley Centre (Jenkins et al., 2009). This data set is on a 25 km rotated pole grid covering GB and Northern Ireland. It is a monthly data set and is spatially coherent. The data used in this study were the base case: the 1960–1990 mean climate and climates for future time-slices 2020, 2030 and 2050. For each future time-slice three emission scenarios; a high, medium and low were used. These represent the IPCC SRES A1FI, A1B and B1 emission scenarios (IPCC, 2000). These data are generated by the HadRM3Q model with an 11 member ensemble of variants with different climate sensitivities (HadRM3-PPE-UK Model Data, 2008). In this study, all crop models were run with the same realization (Number 1), which is the ensemble member with no perturbations, so that the results were directly comparable. This would be similar to the UKCP02 data set but at a higher resolution (Fig. 2).

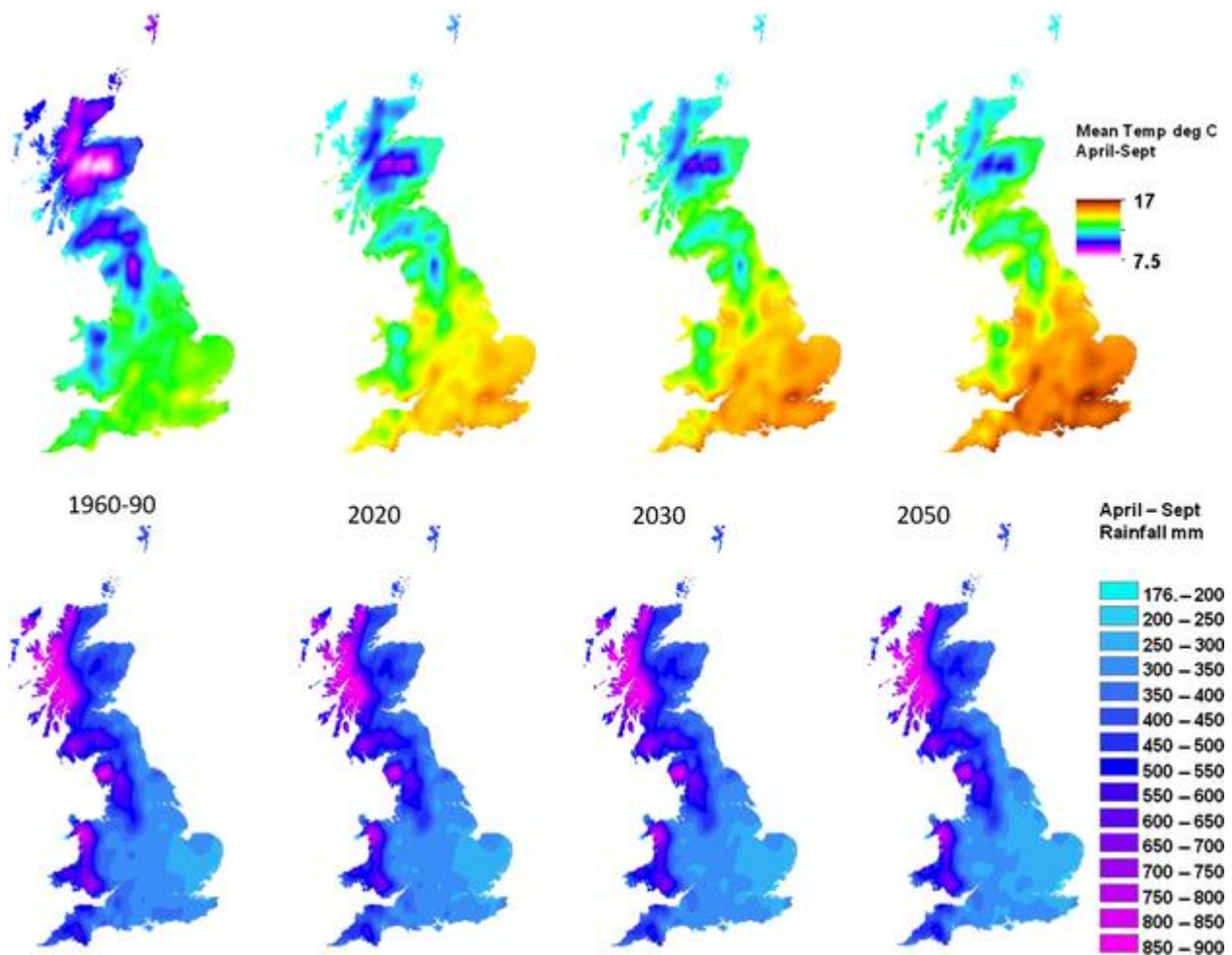


Figure 2 Examples of temperature and rainfall amounts and distributions within Great Britain out to 2050 under the medium UKCP09 emission scenario used to drive the models.

Soil data

The soil data used as input for the models were derived from the Harmonized Soil World Database (HSWD), which provides soil data on a 0.00833 degree grid for the world (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). This database provides ten soil sequences and their areal percentage of each grid block. Each soil sequence is described by its FAO soil name and depth. Physical and chemical parameters for the soil are provided for the topsoil to 30 cm and subsoil for the next 70 cm or the maximum soil depth. The parameters provided include the fraction of gravel, sand, silt and clay, bulk density, fraction of CaCO₃, CaSO₄ and organic carbon, salinity, pH and Cation Exchange Capacity. The dominant soil profile for each grid block was extracted from the database and the total organic carbon for the profile calculated in Mg ha⁻¹ and the soil porosity, wilt point and field capacity calculated using the Campbell method (Campbell, 1985). These parameters were used as model input for each grid block. For soils overlaying chalk and limestone the additional supply of water by

capillary action from ground water was estimated from an experiment in Sheepdrove Farm Berkshire (Finch, 2007). This experiment measured actual evapo-transpiration, rainfall and the water content of the regosol and chalk to a depth of 5 m over a period of 3.5 years. From this data set and capillary pressure curves of chalk samples, the water balance was modelled determining that the effective plant available water was in excess of 1450 mm so for soils over chalk the soil water capacity was set to 2450 mm and the wilt point to 1000 mm (A. Hastings and J. Finch, unpublished results).

Running the models and mapping yield estimates on acceptable land areas

Each model was run for all the soil grid points covering the whole GB area (483 514 points) using each of the meteorological conditions for each time-slice/climate scenario (10 cases). For each soil grid point, the data from the nearest meteorological grid were used in the model and the biomass dry matter yield in $\text{Mg ha}^{-1} \text{ yr}^{-1}$ was used as an input into ArcGis software v10. A yield map for 2010 for each model was constructed by adding 1/3 of the base case 1960–1990 yield to 2/3 of the 2020 high scenario yield as there is no UKCP09 data set for that year.

Land available for bioenergy crops in GB was constrained by a number of physical, economic, social and sustainability factors (e.g. impacts on soil carbon stocks and competition with land for food, according to Sunnenberg et al., 2013). Sunnenberg et al. (2013) produced a series of constraints maps, highlighting where biomass plantations should not be grown. These areas include the following: built areas, transport networks, river and lakes, heritage sites and monuments, designated areas (e.g. special scientific interest), total woodland, peat soils, natural habitats including acid, neutral and limestone grasslands and landcover inside national park with a naturalness score $>65\%$ and a slope $>15\%$. For each 1×1 km data point on the yield map that had one or more constraints the yield in that grid was set to zero. Then summing the biomass yield in all UK grid points, the total yield for each feedstock was calculated. In addition for each grid point, the maximum yielding feed-stock was determined and hence the technical maximum biomass production was obtained for each climate change scenario and time-slice. The histogram of yields for Miscanthus, SRC and SRF species was then prepared for each time-slice (2010, 2020, 2030 and 2050) and for each emissions scenario (Low, Medium and High) to analyse the change in yield and favourable bio-climatic envelope.

The yield of each SRF species was compared for each 1 km² grid and a map of the highest yielding species was generated. The yield of SRF best yield, Miscanthus, SRC willow and SRC poplar were then compared for each 1 km² grid and maps of the highest yielding feedstock species/technique and the maximum biomass yield was produced. This was repeated for each time-slice and emission scenario. Histograms of the yield for each feedstock type were prepared for each time-slice and the mean yield for the entire GB calculated for each feedstock. From the maps of the best yielding feedstock the total area of GB where each is best was tabulated. The mean yield of each feedstock was calculated for each NUTS1 (EU units for terrestrial statistics) region of GB for each scenario and time-slice.

Results

Regional climates in GB are influenced by the Atlantic Ocean, the continental European land mass and latitude. Generally, north-west (NW) regions are exposed to the maritime polar air mass bringing cool moist air and the north-east (NE) regions by the continental polar air mass bringing cold dry air, The south-east (SE) regions experience the continental tropical air mass bringing warm dry air and the south-west (SW) regions are exposed to the maritime tropical air mass which brings warm moist air (Fig. 2). For the growing season out to 2050, the climate exhibits the same geographical influence, but is predicted to warm across GB with a slight decline in precipitation in the south east (Fig. 2).

The yield of each feedstock was calculated for each time-slice and scenario. For all land designated as physically and socio-economically suited to grow dedicated biomass plantations (outside of the constraint mask) yields were modelled and estimated for the 2000–2010 decade (1990–2020 for SRF on 20 year cycle) and harvestable above-ground biomass mapped (Fig. 3). For all biomass crops, yields ranged from zero to a maximum of 17 Mg ha⁻¹ yr⁻¹, and yield was crop type and location specific. An analysis of yields for all of the SRF species showed that Poplar outperformed in all of the other SRF species (Fig. 3) (except for Sitka Spruce in the Scottish highlands and Pennines, but most of these areas are in the constraint mask area, data not shown). Of the two dedicated lignocellulosic crops identified for biomass production in the GB Miscanthus had a higher yield than SRC willow (Table 1) but different yield patterns (Fig. 3), with willow performing better in cooler areas. SRC and SRF poplar had similar mean yields and these were greater than both SRC willow and Miscanthus (Table 1) but with different yield patterns (Fig. 3). However, in detail

some crops gave similar yields per grid block so that there is a choice for the producers. Some other small localized exceptions existed and these were for SRF ash which yielded greater than SRC willow in some central, southerly and south-east areas and Miscanthus in parts of Essex although SRF poplar out yielded SRF ash in all places. A combination of Miscanthus, SRC willow and poplar and SRF poplar produced the greatest GB mean yields and out yielded all other crop types for each designated 1 km² location (Fig. 4).

Table 1 The total yields for each region of the United Kingdom (NUTS1) by crop type

NUTS 1 Region	Land ex constraints (Mha)	Mean harvest yield dry weight biomass (Mg ha ⁻¹ yr ⁻¹)							
		2011 baseline				2051 medium emissions			
		M.x.g	SRC-willow	SRC poplar	SRF poplar	M.x.g	SRC-willow	SRC poplar	SRF poplar
Scotland	1.079	8.25	8.25	12.94	9.07	10.55	8.18	13.97	12.02
North	0.507	9.39	10.51	13.50	8.97	11.04	10.50	14.05	11.95
NW	0.301	11.37	12.10	15.79	10.41	13.18	11.39	14.87	12.66
NE	0.758	8.96	8.28	11.58	10.06	10.40	8.05	11.02	12.81
Wales	0.541	12.47	9.81	13.75	9.94	15.41	8.44	12.71	12.28
E Midlands	1.068	7.66	6.90	9.88	10.52	8.96	7.24	8.78	12.86
W Midlands	0.777	9.09	7.49	10.05	11.45	10.74	6.13	8.71	13.89
E Anglia	0.831	7.37	6.07	8.21	11.62	8.63	5.73	7.16	13.05
SW	1.128	13.10	8.34	11.61	10.61	15.43	7.23	9.92	12.28
SE	1.463	9.41	7.55	9.78	11.51	11.02	6.99	8.34	12.75

SRC, short rotation coppice; SRF, short rotation forestry.

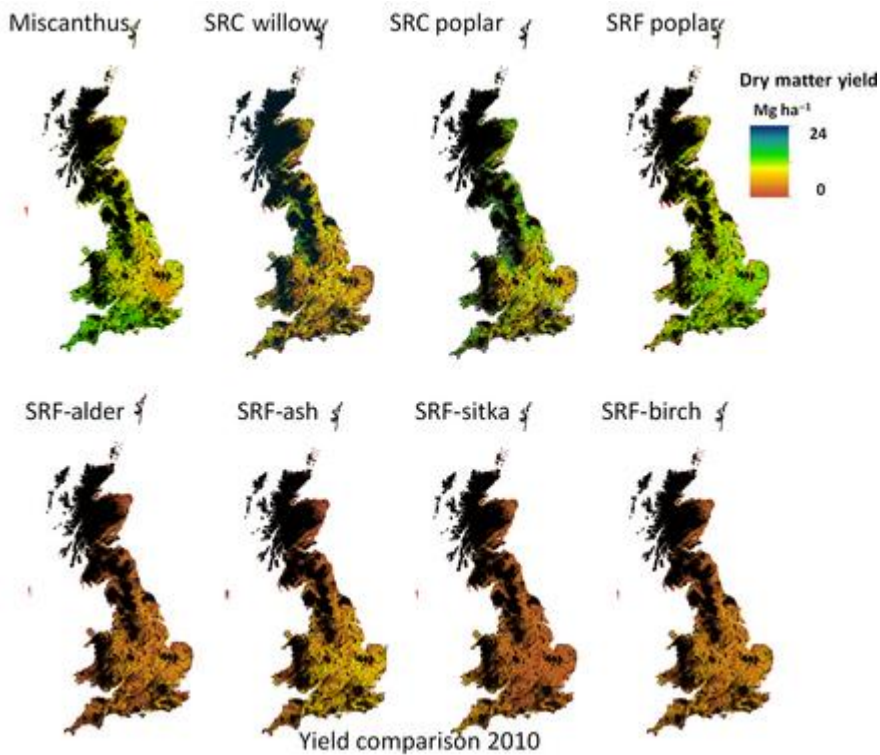


Figure 3 Modelled yields for each modelled biomass plantation type modelled under current conditions and mapped to the land area of Great Britain designated as having the physical and socio-economical capability to grow biomass. The legend shows the colour code of biomass yield and black is the excluded area.

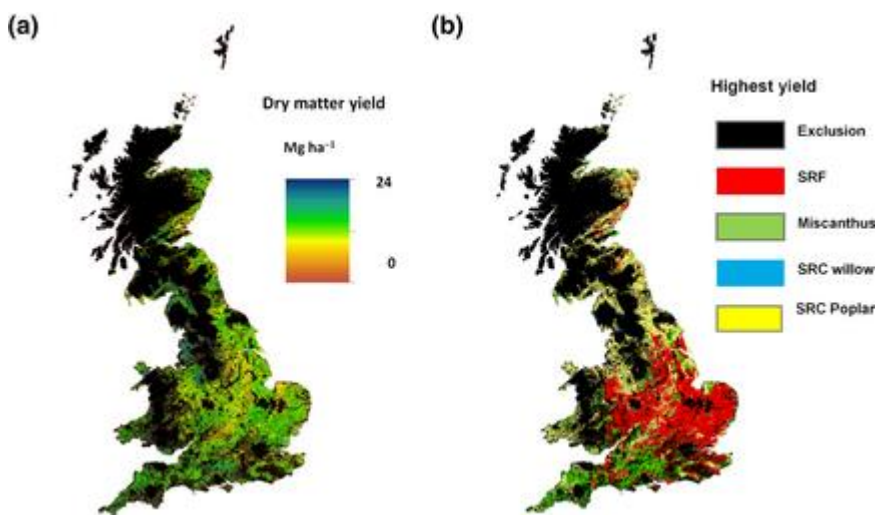


Figure 4 For current conditions, (a) the biomass plantation type giving the highest yield for each 1 km² area and (b) the maximum yield achieved in each 1 km² area of Great Britain. The legend shows the colour code of biomass yield and feedstock with the highest yield. Black is the excluded area.

For yields modelled under future scenarios of climate change additional to the dedicated energy crops for GB, Miscanthus and SRC willow, SRC and SRF poplar as the highest yielders were considered. The example of Miscanthus (Fig. 5) shows that there is a strong spatial variation in yield across the GB with a trend for yield change with time for both the high and low emissions scenario. Figure 5 shows that for Miscanthus the trend towards higher yields is marked with a larger difference between time-slices than between emissions scenarios (Table 2). For this reason, in most of the following results we have chosen to focus on the medium emissions scenario. Considering these four dominant crops, Miscanthus, SRC willow, SRC and SRF poplar, future climate scenarios influenced yield and the relative yield and spatial variation are mapped in Fig. 6. The mean yield for Miscanthus increases as the climate warms from a mean of 9.5 Mg ha⁻¹ in 2010–11.3 Mg ha⁻¹ in 2050 (Table 1). SRC willow mean yield declines slightly from 8.0 to 7.5 Mg ha⁻¹ in 2050 and SRC poplar remains constant at 10.3 Mg ha⁻¹ (Table 1). SRF poplar is on a 20 year cycle so is modelled differently but increases from 10.5 Mg ha⁻¹ to 12.5 Mg ha⁻¹ in 2050 (Table 1). If the maximum yielding feedstock per grid block is taken the mean yield increases from 12.7 Mg ha⁻¹ in 2010 to 14.2 Mg ha⁻¹ in 2050 (Table 1; Fig. 7). The changes in UK mean yield were caused by the yield distribution for each feedstock varying with time, reflecting the geographical climate change (Fig. 8). The areas of GB where each feedstock gives the highest yield changes with time, Miscanthus and SRF Poplar increase and SRC willow and SRC poplar decrease (Table 3). The trend is different in the various NUTS1 regions: Miscanthus increases its yield between 2010 and 2050 in all regions, SRC willow and poplar decreases in the dryer Eastern areas by 2050 and SRF Poplar increases in all areas (Table 4).

Table 2 Mean UK annual dry matter yield per ha of Miscanthus per scenario and time-slice

Time-slice	Low scenario	Medium scenario	High scenario
2010	9.78	9.78	9.78
2020	10.52	10.47	10.39
2030	11.36	11.24	11.06
2050	11.88	11.52	11.13

Table 3 The total area (Mha) of the United Kingdom for the feedstock with the highest dry matter yield

	<i>Miscanthus</i>	SRC willow	SRC poplar	SRF poplar
2010 base case	1.357	0.057	3.593	3.484
2020 medium scenario	2.081	0.044	2.870	3.496
2030 medium scenario	1.690	0.025	1.825	4.952
2050 medium scenario	1.996	0.018	1.699	4.777

SRC, short rotation coppice; SRF, short rotation forestry.

Table 4 Mean yield of each feedstock with time-slice in Mg ha⁻¹ yr⁻¹

	2010	2020	2030	2050
<i>Miscanthus</i>	9.53	10.25	10.99	11.33
SRC willow	8.07	8.13	7.59	7.59
SRC poplar	10.17	10.35	10.35	10.30
SRF poplar	10.55	10.31	13.07	12.68
Best feedstock for each area	12.70	12.71	14.34	14.23

SRC, short rotation coppice; SRF, Short Rotation Forestry.

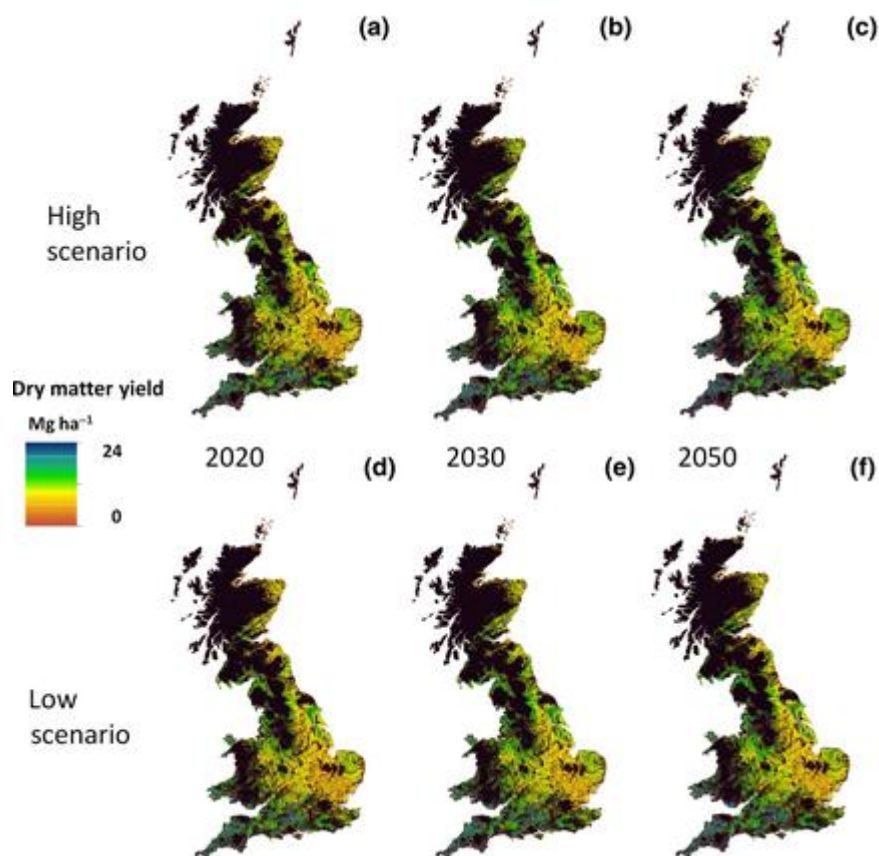


Figure 5 Modelled yields for *Miscanthus* for multiple decades and scenarios. Mean yields are mapped for the decade under (a–c) high emission 2020–2050 and (d–f) low emission 2020–2050 scenarios of climate change. The legend shows the colour code of biomass yield and black is the excluded area.

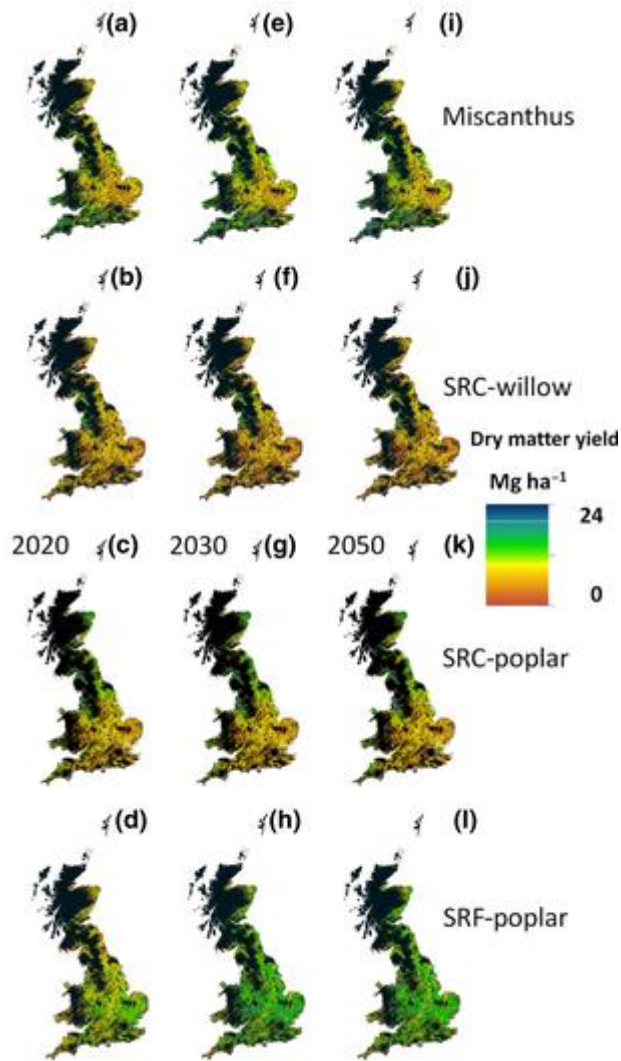


Figure 6 Modelled yields for each biomass plantation type for the future medium emissions scenario of climate change and mapped to the potentially available land. Yields are for (a–d) the 2020s (e–h) 2030s and (i–l) 2050s and for Miscanthus (a, e, i) short rotation coppice (SRC) willow (b, f, j), SRC poplar (c, g, k) and short rotation forestry poplar (d, h, l). The legend shows the colour code of biomass yield and black is the excluded area.

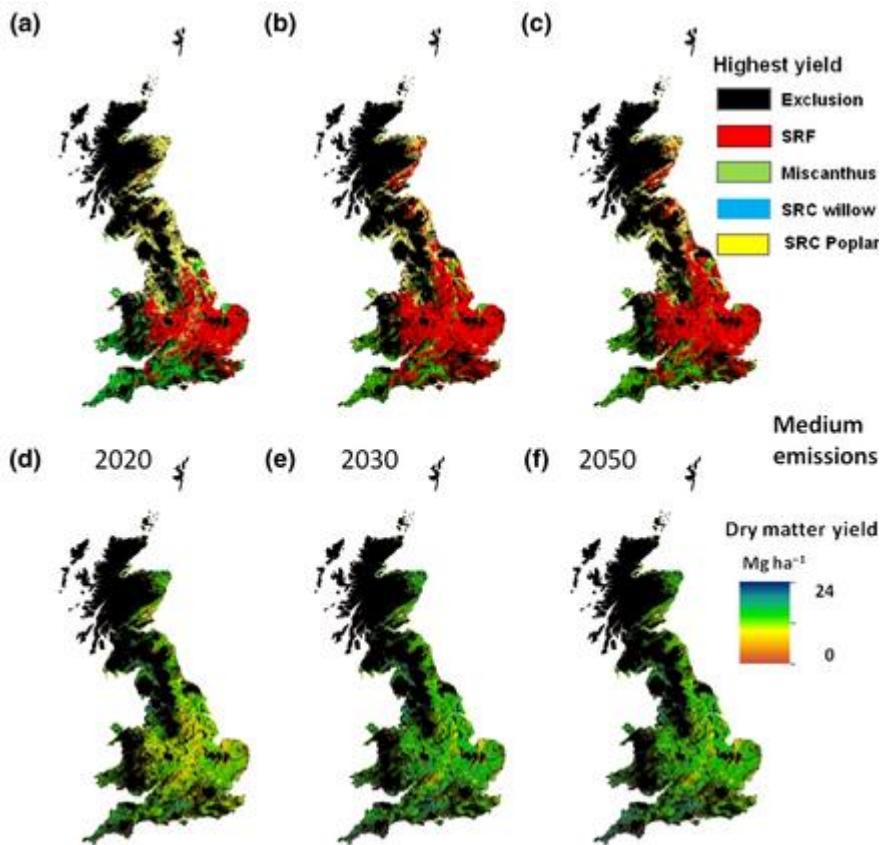


Figure 7 The highest yielding biomass crop (a–c) and the maximum attainable yield (d–f) for each available location (1 Km²) under the medium emission scenario of climate change. Maps are given for decades 2020 (a, d), 2030s (b, e) and 2050s (c, f). The legend shows the colour code of biomass yield and feedstock with the highest yield. Black is the excluded area.

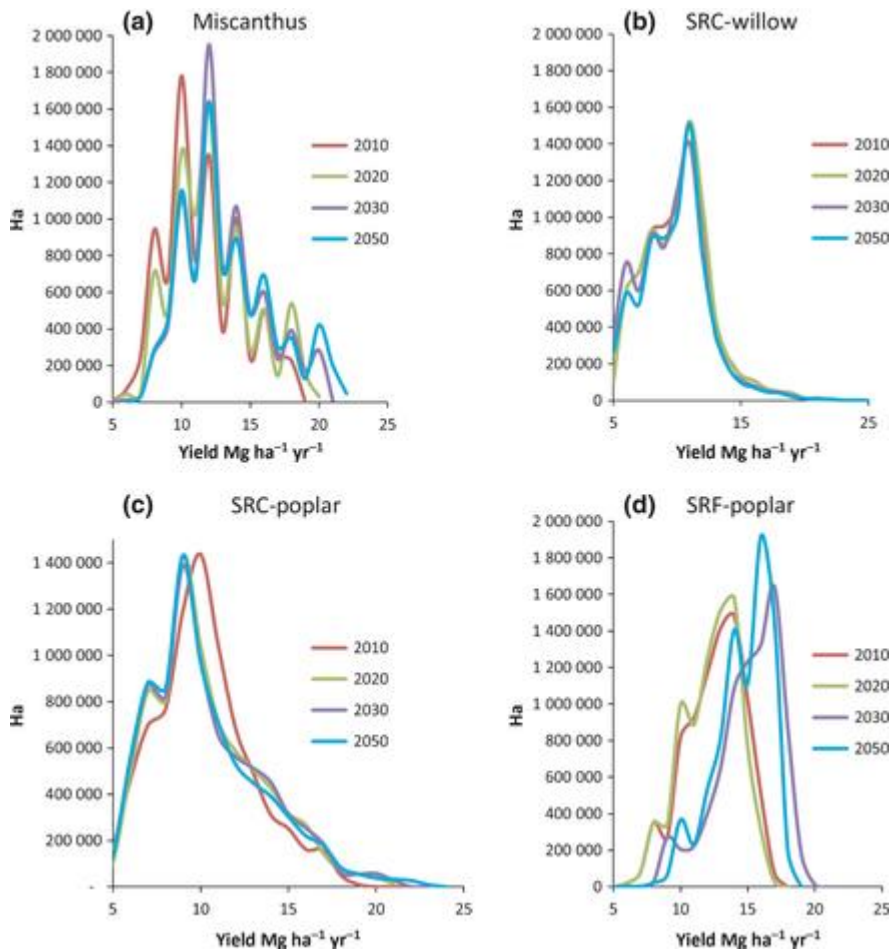


Figure 8 The frequency of total area of potentially available land supporting a given modelled biomass yield under current and future medium emission scenario conditions. Modelled yield (Mg ha⁻¹ yr⁻¹) are reported for (a) Miscanthus (b) short rotation coppice (SRC) willow (c) SRC poplar and (d) short rotation forestry poplar.

Discussion

The potential for GB to generate domestic lignocellulose biomass for the bioenergy market has been modelled for the present day and out to the year 2050 for three different scenarios of climate change using the same meteorological and soil data to drive all models. The most up-to-date plant growth models for each of the feed-stocks were used. Two process-based models, MiscanFor© and ForestGrowthSRC were used for Miscanthus and SRC willow and poplar as they have been calibrated with recent field experiments in the United Kingdom and EU. The model used for SRF was an empirical forestry model based on historical yield

curves as there is as yet little experimental data to parameterize a process-based model for all the SRF species considered in this study. Although this used a different modelling approach to estimate yield, SRF shows large potential in the United Kingdom (McKay, 2011); therefore, it was considered important to include the SRF technique in this study.

CO₂ fertilization was considered in the SRC willow and poplar simulations but not in the Miscanthus and SRF simulations. For C4 plants, CO₂ fertilization has a nonsignificant effect (Leakey, 2009 & Long et al., 2005) but could reduce water use and hence increase yield by delaying the onset of water stress; however, no [CO₂] × temperature × water interaction experiments are available to parameterize & validate MiscanFor©. For C3 plants, CO₂ fertilization has a significant effect in increasing plant growth, and data were available to parameterize and evaluate the ForestGrowth-SRC model (e.g. Liberloo et al., 2009). The yield of SRC responds positively to changes in CO₂ concentration (Tallis et al., 2013) but results here show that yields respond also to interactions with water availability and temperature as has also been suggested by Long et al. (2005). For the SRC willow yields modelled here under different climate change scenarios the CO₂ stimulation is lost across wide geographical areas. Experimentally multifactorial approaches to measure yield changes for changing climates in C3 species have been limited (Mikkelsen et al., 2008; Beiger et al., 2011). But these recent experiments report that the CO₂ fertilization effect on yield may be partially lost when a concomitant air temperature increases was applied especially when large spatial scales are considered (Leuzinger et al., 2011; Zhang et al., 2013) supporting the findings here from ForestGrowth-SRC. The Carbine model, being based on historical yield tables, does not include the CO₂ fertilization effect. Ainsworth & Long, 2005 show in their meta-analysis of FACE experiment that tree species worldwide respond to CO₂ fertilization by up to 28%; however, the SD was the same order of magnitude. In this study, as there are no experimental data to quantify the interaction of plant spacing, canopy closure, water and temperature stress with CO₂ fertilization on all the species of SRF and bearing in mind the findings of Beiger et al. (2011), Long et al. (2005) and in this study ForestGrowth-SRC, the modelling results shown here for SRF do not include that effect but this is identified as an area for future research.

Yields were modelled for the current dedicated biomass crops Miscanthus, SRC willow and poplar and for the first time for contrasting SRF species. SRF poplar was found to be the best yielding SRF species on most

land area of the GB when compared with all selected spp. with the exception of the Scottish Highlands, Pennines and Lake District upland areas, where Sitka spruce grew better. Generally, the yield increased with the climate change. SRC poplar outperformed SRC willow except in the Lancashire and Cumbria and both declined in yields for the future scenarios. SRC poplar was comparable to SRF Poplar which performed better in dryer and warmer areas, probably due to more resilience and less frequent clear-cut harvest than SRC. Miscanthus performed better in warmer and wetter climates such as the SW and Wales and its bioclimatic area increased with climate change.

The GB land area for land meeting certain physical and socio-economical requirements for biomass production (Sunnenberg et al., 2013) was estimated to be 8.5 mha, ca. 50% of the total utilized agricultural area of the United Kingdom in 2012 (DEFRA, 2012). The realizable land area will be smaller to avoid conflicts with food production. Recent estimates suggest that the land available for bioenergy plantations could be between 0.9 and 3.6 Mha in the United Kingdom, this represents 9–35% of land under agricultural production. Considering an energy intensity of biomass to be 18 MJ Mg⁻¹ (Hastings et al., 2009a) and a mean best feedstock yield from this study of 12.7 Mg ha⁻¹, biomass has an estimated potential to supply between 0.21 and 0.83 PJ of primary energy for the United Kingdom. This would rise to 0.24–0.93 PJ by 2050. This is close to the 100–200 TWh per annum at 2050 predicted by the UK Biomass Strategy (DECC, 2012b).

Three different models, MiscanFor© (Hastings et al., 2009a), ForestGrowth-SRC (Tallis et al., 2013) and the ESC-CARBINE model have generated potential biomass supply data for GB from contrasting spp. using the same input data sets for soils and climates. Where possible the modelled yields are supported by field data (Edwards & Christie, 1981; Hastings et al., 2009a; Tallis et al., 2013) and are geographically resolved according to climate soil type. This agrees with knowledge of the origin and physiology of the biomass plant type. For the dedicated biomass crops currently grown in GB (Miscanthus × giganteus and SRC willow) SRC willow out yielded Miscanthus in the wet and cooler regions of the north, particularly the north west, where mean yields were 12.1 Mg ha⁻¹ yr⁻¹. This may reflect the Swedish origin of this genotype (Lindegaard et al., 2011) and the C3 photosynthetic pathway of willow. This has a lower optimum temperature than the C4 pathway (Sage & Kubien, 2007) of the Asian originated Miscanthus which out competed SRC willow in all

other areas (the warmer regions) yielding between 7.4 Mg ha⁻¹ yr⁻¹ in the dry east to 13.1 Mg ha⁻¹ yr⁻¹ in the wetter south west. For SRC willow, these yields and regional trends are similar to other modelled estimates (Aylott et al., 2010 mean 9.7 Mg ha⁻¹ yr⁻¹ and NW most productive) and examples of measured yields from growth trials in the United Kingdom for genotype Joruu are 8.4 (Lindegaard et al., 2011) and 9.1 (Aylott et al., 2008). The same trends in East West regional differences in yield were reported for current breeding trials (Bauen et al., 2010; Macalpine et al., 2011; Anon, 2012;). For Miscanthus, these yields and regional trends are also similar to those reported by Hastings et al. (2009b), using the same model but different climate (CRU 2.1) (Mitchell et al., 2004) and soil data (IGBP-FAO)(Global Soil Data Task Group,2000), and Hillier et al. (2009) using a statistical model for the UK current climate.

When alternatives for the dedicated UK energy crop plantations were considered, poplar grown under SRC and SRF management systems delivered different yields in large areas of the United Kingdom. It is interesting to speculate on why such differences between SRC and SRF poplar emerged in this study. Poplar SRC dominated northern and north eastern areas, traditionally areas for SRC willow. Poplar SRF had highest yields in central and south eastern areas. For poplar SRC *Populus trichocarpa* var. *Trichobel* yields was modelled. This genotype originates in the drier NW USA and is reported (Dimitriou et al. 2009) to have a greater water use efficiency than willow and this is represented in the model (Tallis et al., 2013). The SRF poplar model on the other hand uses generic forestry yield curves for poplar and is not genotype specific. When comparing yields of SRC and SRF poplar, the respective management systems should also be considered increasing the plant spacing of crops of highly productive poplar (as in SRF) is likely to increase their light interception efficiency, while increasing plant densities should benefit less productive genotypes because of their weak potential in canopy closure dynamics. This was shown in previous work reporting that productive poplar plants in wide spacing produced more growth later in the season than those in dense spacing, as a result of a larger proportion of biomass allocated to branches (DeBell et al., 1996; Casella & Sinoquet, 2003, 2007). In addition, SRF will develop deeper rooting systems to access more water and the 3 years cutting cycle of SRC may cause some regrowth impairment.

This modelling study suggests that maximum potential from GB domestic biomass will be achieved by a mix of feedstock types bred for the range of UK climates seen now and expected out to 2050 and a mix of

management strategies. Miscanthus, SRF and SRC poplar and to a lesser extent SRC willow are viable sources covering this climatic range and maximum achievable yield is currently 17 Mg ha⁻¹ yr⁻¹. For the maximum potential land area described in this study (8.5 Ma ha) yields modelled under current climates (2010) give a maximum annual above ground harvestable biomass of 68.1 m dry tonnes (SRC willow) 80.5 m dry tonnes (Miscanthus), 85.8 SRC poplar and 89.1 m dry tonnes (SRF poplar). Nationally, mean yields were 8.07 Mg ha⁻¹ yr⁻¹ (SRC willow), 9.53 Mg ha⁻¹ yr⁻¹ (Miscanthus), 10.17 (SRC poplar) and 10.55 Mg ha⁻¹ yr⁻¹ (SRF poplar).

Except for willow SRC, the geographical trends between yield and biomass type do not change out to 2050. Miscanthus continues to dominate yield in the SW and in the future the NW has high yielding capability for Miscanthus. Poplar SRF continues to dominate in central, Eastern and Northern areas in the further eastern Scotland has high yielding capability for poplar SRF. SRC willow becomes out competed in most areas of NW by Miscanthus and for the whole UK maximum yields of 24 Mg ha⁻¹ yr⁻¹ are achieved under the high emission scenario for 2050.

Short rotation coppice willow and poplar are C3 riparian species and have a high water use. Annual transpiration of SRC is reported to be 40–100 mm more than for Miscanthus (a C4 crop) (Hall, 2003a) and up to 125 mm more than broadleaved forest (Hall, 2003b) on a per unit area basis. Modelled yield using ForestGrowth-SRC match the UK rainfall pattern by a function similar to that suggested by Hall (2003b) (2.18 g biomass for each mm of summer rain) (Tallis et al., 2013). Yields modelled by ForestGrowth-SRC report the stimulation expected from predicted increases in future atmospheric [CO₂] (Ainsworth & Long, 2005; Tallis et al., 2013) and future yields were expected to be stimulated. As expected maximum SRC willow yields were achieved in the high 2050 scenario (22.8 Mg ha⁻¹ yr⁻¹); however, high yielding areas were limited and generally on land with one or more constraint (e.g. >30% SOC and >15° slope).

The Miscanthus × giganteus genotype was modelled in this study as it is currently the variety used in commercial plantations. Being a C4 perennial grass, with an origin in SE Asia it is well adapted to warm wet summers and cold dry winters. This study delivers a yield distribution that matches the conditions of its origin with lower yields in the dryer eastern UK and a larger yield in warmer areas such as the SW and

Wales. As the climate warms through the time-slices, there is a yield increase and thus a larger area where *Miscanthus* is the highest yielder of the feed-stocks considered.

These modelled yields are associated with a number of uncertainties. These include model computational uncertainties reported in Hastings et al. (2009a) for *Miscanthus*, Tallis et al. (2013) for SRC and in Pyatt et al. (2001) for SRF. The driving data set will each have their associated uncertainties. Climate change uncertainties are reported for GB in Murphy et al. (2009). Uncertainties are also associated with the HSWD (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) in homogenizing fine scale soil heterogeneity to a 1 km² grid and although the HSWD gives 10 soil types per grid block, we only considered the dominant soil type in each to reduce the computational time to a reasonable level. In addition, in current and future climates, we did not consider the impact of pests and disease (e.g. rust *Melampsora* spp. in SRC) or variable plantation establishment (e.g. the plot patchiness of *Miscanthus*) regrowth vigour (ageing) (Al Afas et al., 2008; Di Nasso et al., 2010), changes in agronomy practices and changes in genetic stock through breeding efforts. However, the modelling framework and the yield outputs reported here can assist in identifying the most appropriate breeding or agronomy efforts to establish future proof high yields that are location and biomass type specific.

For the United Kingdom and Swedish breeding programmes of SRC willow Karp et al. (2011), an average increase in yield of ca. 2 Mg ha⁻¹ yr⁻¹ from breeding releases between 1974 and 2005 has been reported, similar to the rate of improvement observed in the United States and Canadian breeding programmes (Volk et al., 2011). Extrapolation of this rate of yield increase out to 2050 suggests a 30% increase on the mean UK trials yields for willow (Jorun) giving an estimated mean GB yield of 11.8 Mg ha⁻¹ yr⁻¹ by 2050.

However, recent advances in molecular genetics of willow (e.g. Karp et al., 2011) and poplar (Taylor, 2002; Tuskan et al., 2006; Rae et al., 2009) could accelerate this rate of yield increase suggesting mean commercial GB yields ≥ 12 Mg ha⁻¹ yr⁻¹ may be achievable in the near future. Indeed growth trials across the East West rainfall gradient in GB are already achieving a mean yield in excess of 12 Mg ha⁻¹ yr⁻¹ (Lindgaard et al., 2011; Anon, 2012). However, current commercial yields are ca. 20% less than those achieved in experimental yield trials (Lindgaard et al., 2011) which will bring mean yields back in line with those reported here. Therefore, improvements in agronomy are required to reduce this yield gap (Lobell et al.,

2009). For SRC willow access to permanent ground water can result in a large increase in yield, although this can have a negative impact on aquifer recharge (Hall, 2003b). Planting of SRC willow in areas with readily available water in catchments not over exploited for irrigation and consumption or in which transient flooding needs managing could be an approach to optimize yields.

The potential of these models to predict future yield potential should not be underestimated. In combination with natural phenotypic and genotypic variation, they may be used as predictive tools linked into breeding programmes, identifying likely successful ideotypes for specific climates (Hastings et al., 2009b). There are many genotypes of *Miscanthus* (e.g. Clifton-Brown et al., 2001; Heaton et al., 2008), hundreds of SRC willow (e.g. Aylott et al., 2008; Lindegaard et al., 2011; Macalpine et al., 2011; Volk et al., 2011) and SRC poplar (e.g. Rae et al., 2008; Marron et al., 2005; Monclus et al., 2005) that have been trialled across Europe and the United States. These reveal wide natural genetic variation for traits related to yield that has yet to be fully exploited, reflecting the largely unimproved nature of these 2G crops and identifying large potential for future improvement. For example, the cold tolerance for *Miscanthus* (Farrell et al., 2006) and drought tolerance for *Miscanthus* and poplar (Clifton-Brown et al., 2002; Monclus et al., 2005) varies between genotypes and Hastings et al. (2009b) showed by improving the frost tolerance and drought tolerance of *Miscanthus* to the best observed in trials to date, then the potential yield in the United Kingdom could double by 2050.

The modelling framework described here identifies the potential for a domestic biomass supply to deliver considerable yields from GB land area to contribute to UK renewable energy targets. The GIS-based approach allows spatially defined bio-physical and socio-economical questions to be asked of this supply chain (see additional articles in this volume) and process-based modelling of yields (*Miscanthus* and SRC) gives the potential to ask questions of management, genotype choice and climate change scenarios impacting on the plantation and subsequent supply chain. The key findings suggest that a species and management mix optimized to the regional climatic differences in GB and improvements in breeding and agronomy offer strategies to maximize lignocellulosic supply to domestic bioenergy production now and in the future.

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