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The potential for bioenergy crops to contribute to meeting GB heat and electricity demands

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Abstract

The paper presents a model system, which consists of a partial equilibrium model and process-based terrestrial biogeochemistry models, to determine the optimal distributions of both *Miscanthus* (*Miscanthus* × *giganteus*) and short rotation coppice willow (SRC) (*Salix. viminalis L. x S. viminalis var* Joruun) in Great Britain (GB), as well as their potential contribution to meet heat and electricity demand in GB. Results show that the potential contribution of *Miscanthus* and SRC to heat and electricity demand is significant. Without considering farm-scale economic constraints, *Miscanthus* and SRC could generate, in an economically competitive way compared with other energy generation costs, 224 800 GWh yr^{-1} heat and 112 500 GWh yr^{-1} electricity, with 8 Mha of available land under *Miscanthus* and SRC, accounting for 66% of total heat demand and 62% of total electricity demand respectively. Given the pattern of heat and electricity demand, and the relative yields of *Miscanthus* and SRC in different parts of GB, *Miscanthus* is mainly favoured in the Midlands and areas in the South of GB, whereas SRC is favoured in Scotland, the Midlands and areas in the South of GB.

Keywords: combined heat and power, electricity, greenhouse gas, heat, *Miscanthus*, renewable energy, short rotation coppice

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Introduction

Rapidly growing energy demand and global warming are the two motivations for the potential deployment of bioenergy. Bioenergy has potential energy, environmental and economic advantages over many current energy sources (Schmer *et al.*, 2008), and is recognized as having a potentially important contribution to the UK Government's energy and environment objectives, including energy security and the reduction in greenhouse gas (GHG) emissions (DTI (The UK Department of Trade & Industry), 2003; Taylor, 2008). The potential for using bioenergy crops to reduce GHG emissions and to supply heat and electricity has been explored in many recent studies (Smith *et al.*, 2000a, b; Bauen *et al.*, 2010; Wang *et al.*, 2012a,b), and has been found to have the greatest carbon mitigation potential of all land-based mitigation options examined (Smith *et al.*, 2000a, b). In addition, the availability of more efficient technologies, such as combined heat and power (CHP) plants, provides additional options for bioenergy crops (Wang *et al.*, 2012a). Among bioenergy crops, *Miscanthus* × *giganteus* (*Miscanthus*) and short rotation coppice (SRC; in GB often willow and poplar species e.g. *Salix. viminalis L. x S. viminalis var Joruun*) have received much attention, because these are believed to be the best yielding fast-growing species in the GB (Aylott *et al.*, 2008a; Bauen *et al.*, 2010), have a higher energy ratio of output to input and can be effective in the mitigation of GHGs (St. Clair *et al.*, 2008).

The United Kingdom has an ambitious renewable energy target of a 15% share of renewable energy in total energy by 2020. This target requires 32% renewable electricity and 14% renewable heat (BERR (The UK Department for Business, Enterprise & Regulator Reform), 2008). Therefore, increases in electricity from 19 TWh in

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2006 to 120 TWh by 2020 and in heat from 4 TWh in 2006 to 90 TWh by 2020 are required (Bauen *et al.*, 2010). Meeting these demands will be a challenge; in 2008, biomass accounted for only 2.3% of electricity generation and satisfied less than 1% of heat demand (Bauen *et al.*, 2010). Therefore, a high resolution estimation of the potential contribution of *Miscanthus* and SRC to heat and electricity in GB is necessary. In this study, for the first time, we provide high-resolution estimates of the potential contribution of *Miscanthus* and SRC to meeting heat and electricity demands in GB, using a model system, which includes a partial equilibrium model and process-based terrestrial biogeochemistry models.

Materials and methods

Miscanthus is a C4 species, which can more effectively use sunlight and water than C3 species (Knapp, 1993; Wang *et al.*, 2012b). Its yields peak towards the end of autumn, at approximately 13 tonnes per hectare (t dry matter ha^{-1}) in the United Kingdom (DEFRA (The UK Department for the Environment, Food & Rural Affairs), 2001), and about 67% of this peak yield is harvested in the following spring when the crop has senesced, repartitioned nutrients to the rhizomes and dried. SRC is recognized by the UK Committee on Climate Change as the most suitable energy crop for current GB conditions, and can be grown productively on both former arable and pasture land, with the average yield being roughly 15 t dry matter ha^{-1} yr^{-1} (Andersen *et al.*, 2005; Aylott *et al.*, 2008a, b).

The contribution of *Miscanthus* and SRC to heat and electricity demands was estimated based on a model system, which consists of a partial equilibrium model based on the supply chain of bioenergy crops with life-cycle analysis described previously in Wang *et al.* (2012a) and the process-based terrestrial biogeochemistry models: MiscanFor (Hastings *et al.*, 2009; Wang *et al.*, 2012a) and ForestGrowth-SRC Model (Tallis *et al.*, 2013). In this system, MiscanFor and ForestGrowth-SRC models were used to generate the yields for *Miscanthus* and SRC, respectively, and the partial equilibrium model was used to define how the optimal suitability of two bioenergy to supply heat and nonheating electricity (hereafter referred to simply as electricity) demands described in Taylor *et al.* (2014). The partial equilibrium model is a demand-driven optimization energy model, which maximizes the profit of the whole energy system while ensuring that the energy demand is met (Wang *et al.*, 2012a). The model does not only determine the optimal locations but also the capacity sizes for energy facilities. The main input parameters included maximum theoretical energy potential, energy cost, the efficiency and cost of the energy technologies, transportation cost and energy demand. The projected yields by MiscanFor and ForestGrowth-SRC have shown good agreement with the field observations. The main input parameters for these two models were the solar irradiation, precipitation and temperature, and soil properties such as soil temperature (Hastings *et al.*, 2009; Tallis *et al.*, 2013).

The distribution of yields for *Miscanthus* and SRC was generated using UKCP09 meteorological forcing data (for 2010) (Murphy *et al.*, 2009) and soil data from the harmonized world soil database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). *Miscanthus* is harvested annually and the peak yield estimated by the model was scaled by 0.67 to obtain the available yield due to drying the following spring (Hastings *et al.*, 2014). The rotation of SRC is typically set to 3 years (Armstrong, 1997; Aylott *et al.*, 2008a). The demand data for heat and nonheating electricity were obtained at 1 km resolution by disaggregating local gas and electricity consumption data (DECC (The UK Department of Energy & Climate Change), 2012a) as described by Taylor *et al.* (2014). The resulting heat demand data include energy used for space and water heating, supplied by both fossil fuels and electricity. Cooking and industrial uses of heat were considered ineligible for supply by bioenergy and therefore excluded. The nonheating electricity data consist of electricity used for all nonheating purposes, comprising mainly lighting and appliances in the domestic sector and a wider range including motors, cooling, and ventilation in the nondomestic sector. Domestic and nondomestic heat demand data sets were derived separately because different methods were required, and then combined to give the total (domestic plus nondomestic) heat demand for each grid cell, with a similar procedure for nonheating electricity demand (Taylor *et al.*, 2014).

To examine the maximal capacity of bioenergy use to meet the heat and electricity demands, we assume that demand is first met from bioenergy crops, wherever the bioenergy crops are available, and that other energy sources are then considered, where the availability of bioenergy crops does not satisfy demand. As described in Lovett *et al.* (2013), a constraint map with a high resolution (100 m) was used to mask areas that are unsuitable for bioenergy crops, and thereby determine the potential land areas for bioenergy crops. The constraint map is derived from a Land Suitability Classification system, which is based on a Sustainability Appraisal Framework, and considers absolute prohibitions (e.g. protected habitats and scheduled historical monuments) and relative limits where planting up to certain thresholds would not impinge upon sustainability objectives. The criteria used to determine land suitability can be found in Table 1 (from Lovett *et al.*, 2013).

Bioenergy is assumed to be the feedstock for CHP, which can generate heat and electricity simultaneously, and reduce carbon emissions by up to 30% compared to separate means of conventional generation (e.g. a boiler and power station)

Table 1 Criteria used to determine land suitability

Item	Criteria
Roads, Rivers & Urban areas	No
Slope	≤15%
Monuments & Heritage sites	No
Designated areas	No
Woodland	No
Peat soils	Soil organic carbon > 30%
Natural habitats	No
Improved grassland	No
National Parks and AONBs	No

(DECC (The UK Department of Energy & Climate Change), 2012b). The systematic efficiency of CHP is assumed to be 85% and the ratio of heat to electricity is 2 : 1 (DECC (The UK Department of Energy & Climate Change), 2012b). The potential CHP position is derived from DECC (The UK Department of Energy & Climate Change) (2011). The cost data for CHP were taken from Wang *et al.* (2012a). To allow optimization, all data are then standardized to a 10 km national grid, and only heat and power are considered in this analysis. Alternative use of the land and the farm-scale economics of growing bioenergy crops compared to alternative uses for the land were not considered here, and are described in Alexander *et al.* (2014). In this study, we derive the potential distribution of energy crops from an energy economics perspective. When aggregating the constraint map at 100 m resolution to 10 km, cells with a potential area of less than 3 ha within the larger 10 km cell were excluded as small areas such as these are not viable for energy crop production. The single scenario modelled considered the yield of bioenergy crops grown under present (2010) meteorological and soil conditions with current crop varieties and agronomic practices, current land-use distribution, and the present (2010) heat and energy demand of the United Kingdom.

Results

Strong contrasts in yield are found between *Miscanthus* and SRC across GB. *Miscanthus* grows best in Wales, and the Northwest and Southwest of England, whereas the highest yield of SRC occurs in the South of Scotland, Wales and the Northwest of England (Fig. 1). This is partly due to the different biophysical characteristics of *Miscanthus* and SRC. Tuck *et al.* (2006) derived simple rules of climate and elevation for *Miscanthus* and SRC. SRC has a larger range of elevation and rainfall, and withstands colder temperatures than *Miscanthus*. The distribution maps of heat and electricity demand are rather similar (Taylor *et al.*, 2014). As expected, the highest demand for heat and electricity is seen for large cities (Fig. 2), which have a high population density (Taylor *et al.*, 2014).

The optimal areas for *Miscanthus* growth occur in the Midlands and the parts of the South of GB, whereas the optimal areas for SRC growth occur mostly in Scotland, the Midlands and parts of the South of GB (Fig. 3). The optimal area for *Miscanthus* is larger than for SRC (Table 2), due to *Miscanthus* having a better marginal value than SRC (ADAS, 2008), and the model being cost-based driven (Wang *et al.*, 2012a). The mixed contribution of *Miscanthus* and SRC to heat and electricity is significant (Table 3). With 8 Mha of land area for *Miscanthus* and SRC, the contribution reaches 224 800 GWh yr^{-1} to heat and 112 500 GWh yr^{-1} to electricity, accounting for 66% of total heat demand and

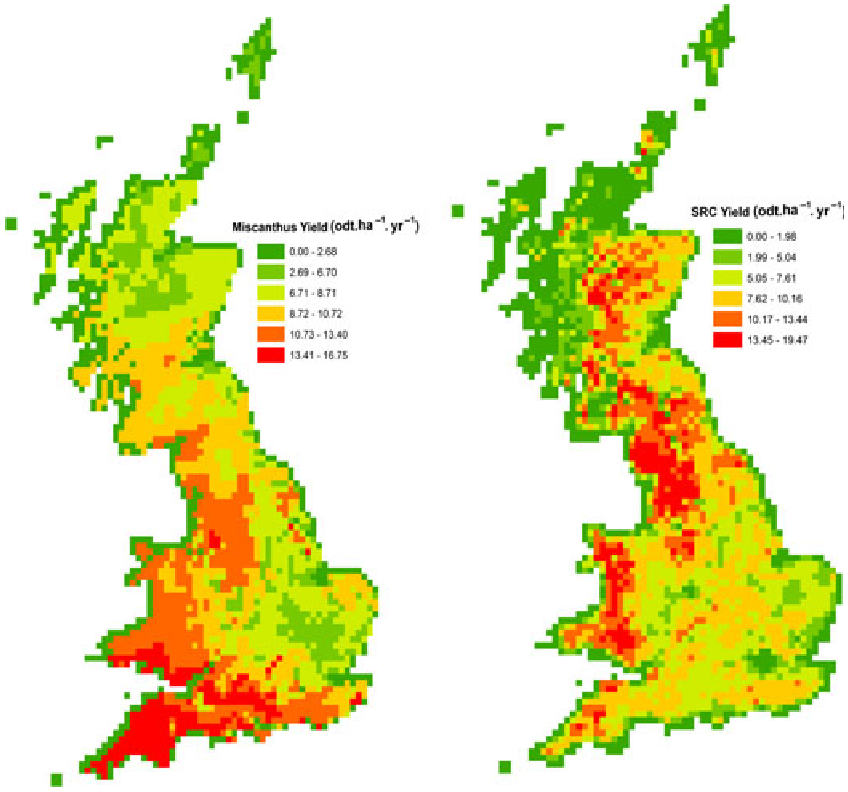

Fig. 1 Yields of energy crops. Left is the yield of *Miscanthus* and right is the yield of SRC.

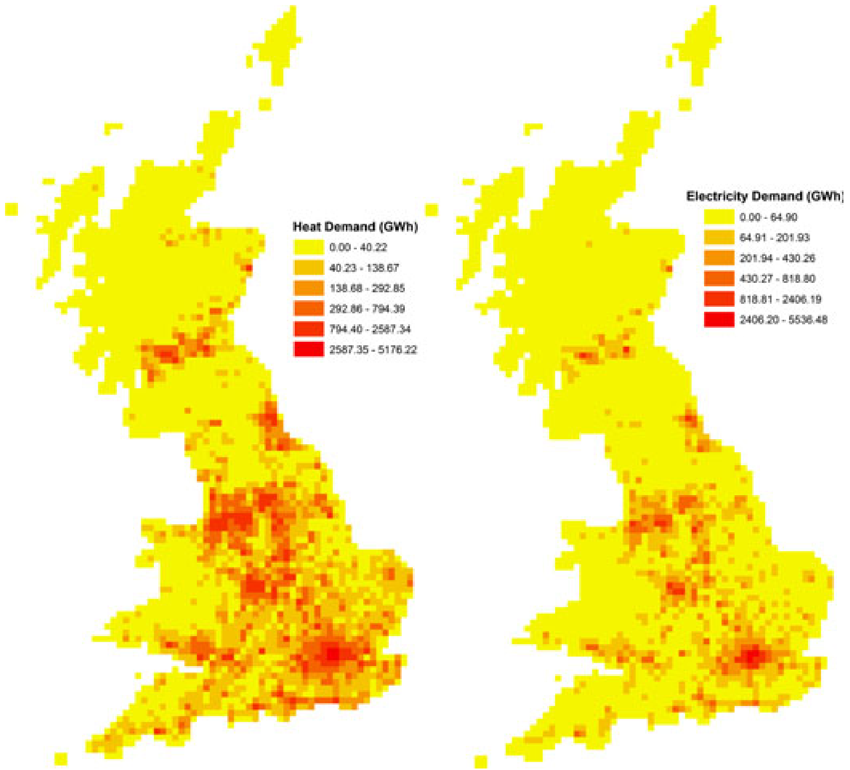

Fig. 2 Heat and electricity demand. Left is the heat demand and right is the electricity demand.

Table 2 Optimal area grown for *Miscanthus* and SRC

Miscanthus area grown (Mha)	SRC area grown (Mha)	Total area grown (Mha)
4.7	3.3	8.0

62% of total electricity demand, respectively, although this analysis does not include the farm level economic viability of bioenergy supply (see Alexander *et al.*, 2014).

Discussion

To meet the United Kingdom's 15% renewable energy target by 2020, it is estimated that biomass needs to contribute 8% of renewable electricity and 60% of renewable heat (BERR (The UK Department for Business, Enterprise & Regulator Reform), 2008). Without considering farm-scale economic constraints or other land use, *Miscanthus* and SRC could generate economically competitive 224 800 GWh yr^{-1} heat and 112 500 GWh yr^{-1} electricity, accounting for 66% of total heat demand and 62% of total electricity demand respectively. Andersen *et al.* (2005) estimated that 5% uptake of SRC in the Scotland would provide an electricity production potential of about 163 MWh yr^{-1}.

The optimal spatial distribution for growing *Miscanthus* and SRC is obviously largely driven by the distribution of heat and electricity demand, the distribution of yields of *Miscanthus* and SRC, and the potential locations of CHP plants. The potential spatial distribution of *Miscanthus* and SRC energy crop areas to meet the demand is an important step in determining the ultimate distribution of these crops, when farm-scale economics are taken into account. If the potential distribution of crops or attainable yield changes in response to environmental change, the optimal area might also change, as may the suitability of each crop compared to the other. The dynamically determined distribution of crop areas also provides a dynamic framework to estimate GHG emissions from land-use change, as advocated by Melillo *et al.* (2009), rather than the use of static frameworks employed elsewhere.

Energy crops are mostly grown in high yield areas, in which the production cost is relatively low. The high-yield areas chosen reduce the deployment of energy crops on existing land with a natural ecosystem, and thus decrease potential GHG emissions from direct land-use change (St. Clair *et al.*, 2008; Hillier *et al.*, 2009), although this will result in competition with food crops (Valentine *et al.*, 2012) and could lead to indirect land-use change elsewhere (Fargione *et al.*, 2008). Using

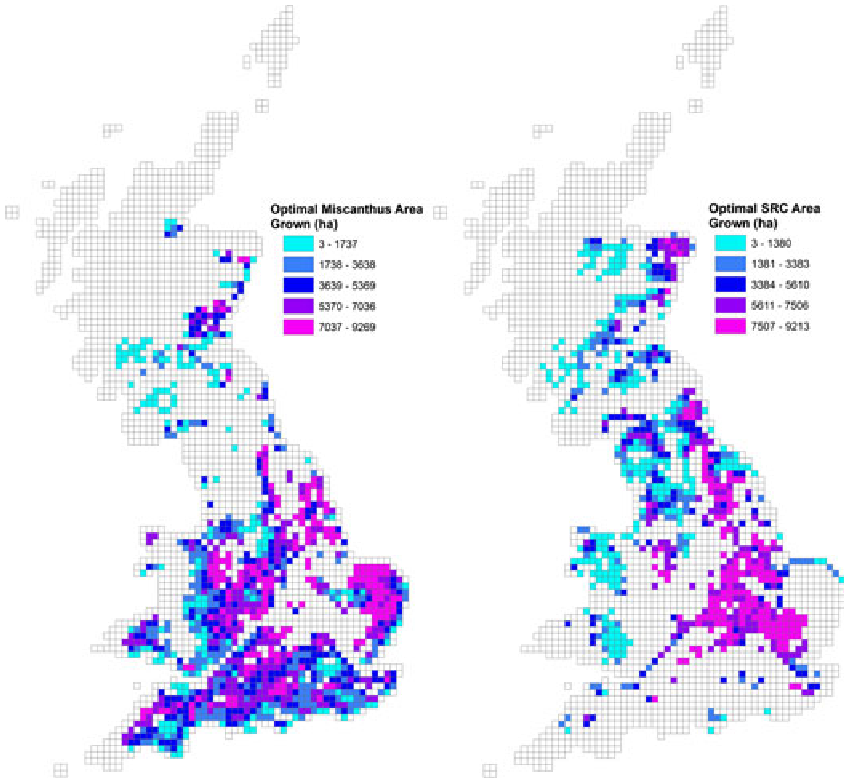

Fig. 3 Optimal area grown for bioenergy crops.

Table 3 Contribution to electricity and heat demand

Heat (GWh yr^{-1})	Electricity (GWh yr^{-1})
224 800 (66%)	112 500 (62%)

biomass for energy is likely to have both positive and negative competitive effects on food production and therefore on land use, although the reasons for growing crops for bioenergy are complex (Smith *et al.*, 2010). Alternatively, energy crops could be grown on land less suitable or unsuitable for food crops (Valentine *et al.*, 2012). The economics of growing crops for energy or for food are considered in Alexander *et al.* (2014). The distribution of energy crops has implications for low-carbon sustainable development in the United Kingdom, which may require the systematic deployment of energy crops, rather than sparse deployment; in the United States, Heaton *et al.* (2008) reported that using *Miscanthus* to meet US biofuel goal will require less land if managed systematically than if allowed to develop unmanaged.

The deployment of energy crops will result in the emission of some life-cycle GHGs. Life-cycle GHG emissions have a strong relationship with initial soil carbon stocks (Hillier *et al.*, 2009) and the land use they replace, as well as the agricultural management during their growth (Wang *et al.*, 2012b). The cost of the life-cycle GHG emissions will impact the final optimal deployment of energy crops (Wang *et al.*, 2012b). The integration of this cost would require additional considerations: the possible ways of combining the cost include (i) setting a carbon cap for the energy crops, and/or (ii) translating the GHG cost to an economic cost, and then using the GHG emissions as a term in the partial equilibrium model.

In addition to the impact on life-cycle GHGs, the deployment of energy crops will also impact other ecosystem services. *Miscanthus* had higher ground flora diversity during the first 3 years after establishment compared with conventional cash crops (Semere & Slater, 2007), and had positive impacts on spider, beetle and earthworm diversity (Christian *et al.*, 1997). The environmental impacts of deployment of energy crops are further considered in Milner *et al.* (2013).

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