

Land Use Implications of Increased Biomass Production Identified by GIS-Based Suitability and Yield Mapping for *Miscanthus* in England

Andrew A. Lovett · Gisela M. Sünnerberg ·
Goetz M. Richter · A. Gordon Dailey ·
Andrew B. Riche · Angela Karp

Published online: 29 January 2009
© Springer Science + Business Media, LLC. 2009

Abstract The need for climate change mitigation and to meet increasing energy demands has led to a rise in the land area under bioenergy crops in many countries. There are concerns that such large-scale land conversion will conflict with food production and impact on the environment. Perennial biomass crops could be grown on more marginal agricultural land. However, for sustainable solutions, biomass yields will need to be sufficient and the wider implications of land-use changes considered. Here, focusing on *Miscanthus* in England as an example, we combined an empirical model with GIS to produce a yield map and estimated regional energy generation potentials after masking out areas covered by environmental and socio-economic factors which could preclude the planting of energy crops. Agricultural land quality and the distributions of currently grown food crops were then taken into account. Results showed that: (i) regional contrasts occur in the importance of

different factors affecting biomass planting; (ii) areas with the highest biomass yields co-locate with food producing areas on high grade land, and; (iii) when such high grade land and unsuitable areas are excluded, a policy-related scenario for increased planting on 350,000 ha utilised 4–28% (depending on the region) of lower grade land and would not necessarily greatly impact on UK food security. We conclude that the GIS-based yield and suitability mapping described here can help identify important issues in bioenergy generation potentials and land use implications at regional or finer spatial scales that would be missed in analyses at the national level.

Keywords Biomass · Land-use · GIS · Suitability maps · *Miscanthus x giganteus*

Introduction

The development of renewable sources of energy for helping to secure future energy supplies and for mitigating climate change is recognised by governments world wide as a vital part of the global sustainability agenda. Bioenergy from crops has been identified as an important contributor in the portfolio of technologies that will be required to meet these targets, and large-scale land use change to bioenergy production is already occurring in many areas of the world.

In the UK, government incentives have been introduced to encourage establishment of bioenergy crops (e.g. the Energy Crops Scheme, ECS, [30]) and the area of land under such crops is increasing. Approximately 7,500 ha were established under this scheme in England alone between 2001 and 2007. If future target obligations for both power generation and liquid transport fuels are to be

A. A. Lovett · G. M. Sünnerberg
School of Environmental Sciences, University of East Anglia,
Norwich NR4 7TJ, UK

A. Karp
Centre for Bioenergy and Climate Change, Rothamsted Research,
Harpenden, Hertfordshire AL5 2JQ, UK

A. B. Riche · A. Karp (✉)
Centre for Bioenergy and Climate Change,
Plant and Invertebrate Ecology Department,
Rothamsted Research,
Harpenden, Hertfordshire AL5 2JQ, UK
e-mail: angela.karp@bbsrc.ac.uk

G. M. Richter · A. G. Dailey
Centre for Bioenergy and Climate Change,
Soil Science Department, Rothamsted Research,
Harpenden, Hertfordshire AL5 2JQ, UK

met, large areas of land (estimated at circa 350,000 ha and 750,000 ha, respectively) will be needed to supply the necessary feedstocks [18].

There have been growing concerns that the full implications of large scale land conversion to bioenergy crops have not yet been fully thought through [44]. In particular, growing first generation bioenergy food crops for liquid biofuels is currently the subject of considerable controversy world-wide. Most of the concerns revolve around direct competition with land for food production, the indirect consequences of land displacement and the failure of first generation biofuel chains to achieve positive carbon balances and significant GHG reductions [26, 40]. However, there have been counter-arguments. Non-food parts of food crops (e.g. wheat straw and maize stover) can be used as co-product streams for biofuels and anticipated gains in maize yield over the next 10 years could arguably meet the world's growing demand for food, feed, fibre and fuel, with minimal or no expansion of the land area under maize cultivation (e.g. [11, 29]).

Perennial biomass crops, such as rhizomatous grasses and fast growing trees are non-food crops that have the potential to offer sustainable bioenergy production [27]. Life cycle analyses of fuel chains for these crops indicate higher energy gains and greater GHG reductions than those associated with first generation bioenergy crops [1, 36, 45]. However, plantings of perennial biomass crops remain in the ground for successive harvests over *circa* 25–30 years. This effectively prevents land from providing other functions, including food production, which is an important ecosystem service tightly linked to land quality.

To help relieve potential conflicts over land use, the planting of perennial biomass crops on more marginal and idle land has been encouraged [5]. However, most trials have been conducted on experimental sites and it is not yet clear whether crop production for energy with current cultivars on less prime land will produce sufficient yields to encourage farmers to sign up for bioenergy planting contracts [42]. It also not clear what the implications of converting this land to perennial crops might be for other existing ecosystem goods and services such as biodiversity, water resources, landscape aesthetics and cultural heritage. These are particularly important issues for many countries, such as the UK, where urban areas and farmland are in close juxtaposition, total land areas are restricted and intensive farming has reduced the quality of the environment, for example resulting in declines in farmland birds [38].

The perennial biomass crops *Miscanthus* (*Miscanthus x giganteus*) and short rotation coppice (SRC) willow (*Salix* spp), that are both commercially grown in the UK, are much taller (3 m to 5 m) than most arable crops and deeper rooting. Depending on the land use replaced, they may

impact on the character and visual appearance of the landscape, on biodiversity and on water availability (e.g. [39]). Thus, although bioenergy production from perennial biomass crops has many potential benefits, decision makers will have to face the dilemma that land conversion to these crops may reduce, even displace, and certainly change, other important products and services of the existing land. The potential allocation of land to bioenergy crops is usually modelled on the basis of yield potential. Such mapping utilises physical constraints to yield production (temperature, soil and water limitations) in order to locate areas of optimal production [2, 10, 35, 37]. However, these methods do not take into account other land-use and policy restrictions on planting, as well as impacts on the types of ecosystem services described above.

Our aim, therefore, was to provide a more holistic method of analysing the implications of land allocation to biomass cropping which incorporated yield variations and other land-use characteristics. To achieve this objective we integrated biophysical (e.g. soil, water, temperature), socio-economic (e.g. urban, cultural heritage) and environmental (e.g. nature, grassland, landscape character) data sets. Particular attention was given to the implications of planting 350,000 ha of biomass crops as proposed in relevant policy documents in the UK [18]. The results are discussed in terms of the pressures on land-use in different regions of England, however, the general method has wider applicability.

Methods

Figure 1 illustrates the overall approach adopted, which was, first, to use a GIS to map variations in *Miscanthus* yield and feedstock supply across England and, second, to mask out those areas which were considered unsuitable on particular grounds. In the final step we examined the uses of the remaining land in order to explore what the consequences would be of converting it to meet bioenergy targets. Initially, areas where the crop would not be grown due to nine absolute factors (see Suitability Mapping section) were excluded. Subsequently, areas covered by two secondary factors (where there were reasons for avoiding extensive planting) were also excluded. Information from the national Agricultural Land Classification [15], was then used to refine these results by restricting attention to the two grades of land on which most existing biomass crop planting is concentrated. Finally, the extent of currently grown food crops on these remaining areas of land was identified and compared with their energy generation potential under *Miscanthus*. Further details of these input data and the processing steps are given below:

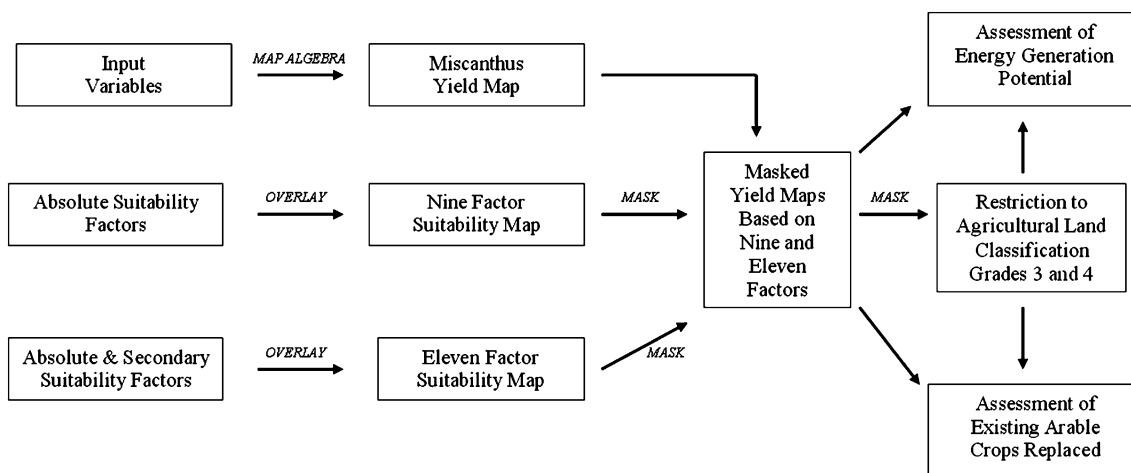


Fig. 1 Schematic outlining the approach adopted

Data Sources

Digital map data for the study were obtained from a range of sources including the EDINA AgCensus, Digimap and UK Borders services at the University of Edinburgh [20] and the MAGIC geportal supported by several government agencies [28]. A few of the data used were reported for 1 km or 2 km grid squares, but most were at effective resolutions ranging between 25 m and 125 m. Aggregating all of the data to the coarsest resolution would have resulted in a significant loss of information and produced some measures (e.g. for slope) that were not especially meaningful, so instead all the different layers were converted to representations on a 100 m raster grid. This size of unit (1 ha) was selected as a suitable compromise for generalisation given the characteristics of the majority of the data sources and the overall extent of England (13 M ha). Most raster and vector layers were converted to this resolution on a majority area basis using the ArcGIS Version 9 software [22]. Where the available data were in numerical form (either percentages or totals) for rather coarser units (e.g. 1 km or 2 km grid squares) then the approach taken was either to apportion totals across 100 m cells on the basis of area or to give all of these cells in a larger unit the same value (e.g. an estimated Miscanthus yield per ha).

Yield Mapping

A map of harvestable Miscanthus yield (oven dried tonnes, odt) was generated by implementing a map algebra analysis [3] in ArcGIS. This involved combining coefficients from a multiple regression equation [37] with 1 km resolution variables derived from the WorldClim database [47] and the NSRI NatMap 1 km soil database [33]. The four agro-climatic and soil variables used to predict harvestable Miscanthus yield were: (1) precipitation during the April

to October growing season (positive effect); (2) precipitation during the October to February post-maturity and pre-harvest period (negative effect); (3) mean temperature during the April to September growing season (positive effect); (4) Available Water Capacity in soil (AWC, positive effect). Results from this analysis took the form of yield estimates on a 100 m resolution raster though, as explained above, all of the cells in the same 1 km square had identical values.

The empirical model developed by Richter et al. [37], based on 67 experimental yield data across the UK, predicted yields in the range between 5 odt ha⁻¹ and 18 odt ha⁻¹ with an error of about 2 t ha⁻¹ (r²=0.51). This model was based on measured AWC or values estimated from a pedotransfer function (PTF) using primary data for mineral soils. AWC data taken from the NatMap database were on average 20 mm lower than these and did not relate well with observed yields and underestimated yields [37]. For the purposes of the map algebra calculations we therefore expanded the PTF [46] to estimate AWC in the profile (AP_PTF) from soil texture, bulk density and organic matter. We assumed a maximum rooting depth of 1.5 m unless otherwise stated, which is a conservative estimate for Miscanthus [32]. The set of rules considered four different soil groups: deep non-gleysols, shallow non-gleysols overlying porous rock, and deep gleysols and shallow gleysols above hard rock and sediments. AWC is the water retention between field capacity (FC) and wilting point (WP, -1,500 kPa), and water content at FC was estimated at -10 kPa for gleysols, and -33 kPa for any other soil. AP_PTF is the sum of horizon-specific AWC up to depth of rock, and water from porous rock was approximated for those soils classified as HOST classes 1 to 3 [4]. AWC of porous rock was assumed to be between 10 vol.% (chalk) and 5 vol.% (oolitic limestone, sandstone) and was estimated for the layers exceeding depth of rock to

the maximum profile depth. For shallow gleysols the PTF was extended to the depth of profile of the porous sediments recorded in the database.

Suitability Mapping

The selection of factors considered in the analysis was informed by a review of previous studies (e.g., [6, 8, 13]) and several discussions with officials involved in current planting support schemes. Eleven characteristics were identified as factors that would result in land being considered unsuitable for planting perennial biomass crops. These were classified into two categories: absolute and secondary. Absolute factors (see 1–9, below) were considered to preclude any opportunity for energy crop planting and included physical features such as urban areas, rivers, lakes and steep slopes, as well as areas of natural or cultural designation, such as key habitats, nature reserves and heritage sites. In contrast, secondary factors (see, 10 and 11 below) were regarded as areas where planting perennial biomass crops would not be encouraged but also not necessarily excluded, e.g. general impact on sensitive landscapes or grassland. Details of the individual layers included in the analysis are as follows:

1. *Soils*: Areas with suitable soils for biomass crops were identified using information on the most common soil series in each 1 km grid cell of the NatMap 1,000 database [33]. Organic soils (e.g. with a peat layer in the profile) were excluded because of the carbon loss that would occur through planting in such areas, as well as those which contained industrial or artificial materials (man-made soils; series codes in the 5,000 s) or where there was insufficient information on water capacity to make a yield estimate.
2. *Natural Habitats*: In order to exclude areas of existing importance for wildlife and nature conservation the boundaries of a range of Biodiversity Action Plan (BAP) priority and semi-natural habitats were downloaded from the Natural England web site [31]. The habitat categories excluded were: Blanket Bog; Coastal & Floodplain Grazing Marsh; Coastal Sand Dunes; Coastal Vegetated Shingle; Fens; Lowland Calcareous Grassland; Lowland Dry Acid Grassland; Lowland Heathland; Lowland Meadows; Lowland Raised Bogs; Maritime Cliff and Slope; Mudflats; Purple Moor Grass Rush Pastures Reedbeds; Saline Lagoons; Undetermined Grassland; Upland Calcareous Grassland; Upland Hay Meadow; Upland Heathland. As all of these habitats were regarded as unsuitable for energy crop planting they were combined into a single map layer.
3. *Woodland*: Planting biomass crops to replace existing woodland would not be financially supported because of the undesired environmental effects incurred, e.g. negative GHG balance [43]. The extents of existing woodland areas were defined by combining Ancient Woodland boundaries from the MAGIC server with details from the Forestry Commission National Inventory of Woodland and Trees [25, 28]. These vector polygons were combined to produce a single raster grid.
4. *Slope Steepness*: An analysis of sites where Miscanthus planting took place in 2001–6 under the ECS indicated that 98.6% of these had a maximum slope angle less than 15%. This limit is also in agreement with terrain analysis for planting sugar cane [41]. Ordnance Survey Panorama digital elevation models (50 m grid cell resolution) were obtained from Digimap [20] and the percentage slope calculated in the ArcGIS software. Further processing was conducted to identify the steepest 50 m grid cell slope in each 100 m grid cell (i.e. the greatest of the four constituent values). Grid cells with a slope of 15% or greater were classed as unsuitable on the grounds that the land would be difficult for planting/harvesting.
5. *Urban Areas*: Boundaries were extracted from the Ordnance Survey Meridian data obtained via the Digimap Service [20]. These lines were edited to form polygons and also exclude any internal open spaces (e.g. parks).
6. *Major Rivers*: Lines representing large rivers (FC=6,225) were extracted from the Ordnance Survey Meridian data obtained via the Digimap Service [20]. These lines were buffered by 100 m before being converted to raster grids.
7. *Lakes*: Boundary lines (FC=6,255) were extracted from Ordnance Survey Meridian data obtained from Digimap [20]. These lines were edited to form polygons before being converted to raster grids.
8. *Designated Areas*: As with the natural habitats category, these types of areas would be excluded from biomass crop planting on nature protection grounds. Boundaries of the following designated areas were obtained from the MAGIC and Natural England websites mentioned above. All of the 100 m grid cells containing the following areas were considered unsuitable for energy crop planting: Local Nature Reserves; National Nature Reserves; Ramsar Sites; Sites of Special Scientific Interest; Special Areas of Conservation; Special Protection Areas.
9. *Cultural Heritage*: A number of concerns have been expressed about the potential negative implications that increased biomass crop planting could have for cultural heritage [21]. Information was therefore obtained from the MAGIC website or directly from English Heritage on the locations of the following

features: Doorstep Greens; Millennium Greens; Historic Parks & Gardens; Scheduled Monuments (National Register); Registered Battlefields; World Heritage Sites. The two types of green were identified by point grid references so these were buffered to create 100 m radius circles before being converted to raster grids. All of the other features were defined as polygon boundaries. Any grid cells containing the six types of feature were considered unsuitable for energy crop planting.

10. *Landscape Sensitivity*:—Studies such as REvision 2010 [6] and the Devon Miscanthus Opportunities Statement [8] have used classifications of Joint Character Areas (JCAs) to incorporate landscape considerations into GIS analyses. A tabular assessment of potential landscape impacts from energy crop planting has been published for each JCA in England by DEFRA [13] but this information is not easy to convert into a graded suitability scale. It was therefore decided to treat landscape sensitivity as a secondary factor in the analysis. Boundaries of four types of areas where landscape considerations are important (Areas of Outstanding Natural Beauty, Environmentally Sensitive Areas, Heritage Coastlines and National Parks) were obtained from MAGIC [28] and combined into a 100 m resolution raster representation.
11. *Improved Grassland*: The current Miscanthus guidance document for ECS applications [30] includes a statement that planting Miscanthus on uncultivated land (during the past 15 years) or semi-natural habitats requires assessment under the EIA (Agriculture) Regulations 2006. There is also a cross-compliance requirement that the national area of permanent pasture should not decline by more than 5% from 2003 levels [12]. This reflects a concern that ploughing grassland to plant crops would increase carbon emissions [43]. Taken together, these factors suggest that grassland should also be treated as a secondary factor to assess suitability.

The 2 km resolution June Agricultural Survey data record 2.98 M ha of permanent grassland in England as of mid 2004. However, a disadvantage with these data is that they cannot be used to reliably estimate a 100 m resolution coverage. An alternative definition is the 25 m raster improved grassland layer in Land Cover Map 2000 [7]. This is based on satellite imagery for earlier years and has a total area for England of 3.02 M ha. This correspondence was considered sufficiently close for the purposes of the analysis, so the LCM data were converted to a 100 m resolution grid applying a majority rule to represent the grassland constraint.

In addition to the above 11 factors, we also considered the national Agricultural Land Classification (ALC, [15]), which provides an integrated assessment of all land quality parameters and suitability for different uses. This classification grades farmland from 1 (excellent) to 5 (very poor), with 2.2 M ha in Grades 1 and 2, 6.3 M ha in Grade 3 (approximately equally divided into Grades 3a and 3b), 1.8 M ha in Grade 4 and 1.1 M ha in Grade 5. An analysis of sites where Miscanthus planting took place in 2001–6 under the ECS indicated that 78.7% of these were on Grades 3 and 4, reflecting decisions by farmers to use better quality land for crops with higher returns. A further stage in the suitability mapping, therefore, was to restrict the area of potentially available land to ALC Grades 3 and 4.

Assessment of Miscanthus Planting Implications

First a yield map was generated on the basis of the input variables (Fig. 1). Once the separate suitability layers had been generated they were overlaid in the ArcGIS software and calculations were carried out to determine the land excluded and the areas remaining that could be considered suitable for planting Miscanthus. Initial analysis focused on the absolute factors (1–9) and the combination of these was applied to the yield map as a mask so that the biomass production potential on the remaining land could be estimated. In a second analysis the landscape sensitivity and grassland suitability factors were incorporated as well so that yield estimates based on an 11 factor mask were obtained. Both of these analyses were then further refined by restricting attention to land that was also classified as ALC Grades 3 and 4.

Once the integration of yield and suitability mapping was completed, the remaining suitable land distribution was compared with that of existing crops using 2 km resolution June Agricultural Survey data for 2004 (the most recent available from the AgCensus Service, [20]) to assess what land-use would be replaced by planting Miscanthus. For each 2 km grid cell the hectares of land identified as potentially appropriate for Miscanthus planting were divided by the total arable cropping area (i.e. crops, bare fallow, set-aside and temporary grassland) recorded in the June Survey and this proportion was then multiplied by the amount of winter wheat or oilseed rape (chosen as examples of common arable crops in England) to produce a simple estimate of the amount of the food crops that would be lost if Miscanthus was grown instead. The Miscanthus yield totals for the potentially suitable land were also converted to energy supply estimates by applying published generation efficiencies and official statistics on electricity consumption.

Results

The total area of England used as the starting point in the analysis was calculated in the GIS as 13.04 M ha. The results of yield and suitability mapping of this total area were examined with respect to England's nine government regions, which are important administrative units for strategic land use and economic planning (including targets and policies regarding renewable energy generation).

Table 1 (second column left) shows the areas of suitable land remaining in each of the government regions after the first nine absolute factors were applied in the analysis. Excluding the areas covered by any of these factors reduced the available land to 7.77 M ha (59.6% of England). The results showed considerable variation in the total amounts of suitable land available (highest: South-West with 1.37 Mha and lowest: North-East with 0.38 Mha, not including the London region) and in the proportion of land excluded between regions (e.g. less than 30% of the East Midlands or East of England was excluded, but more than 55% of the North East or North West). There was some overlap between the different layers applied in the analysis (Fig. 2) so that, for example, of the 9.5% of England classed as having unsuitable soils, 6.7% was also covered by one or more of the other eight factors. Of the latter the most significant were urban areas (14.6% of England), slope steepness (9.5%), natural habitats (8.4%), woodland (8.3%), and designated areas (6.5%).

Extensive planting of *Miscanthus* in environmentally sensitive landscapes, or improved grasslands could result in major changes in views, landscape character, natural habitat (and thus biodiversity) and water availability typical of a

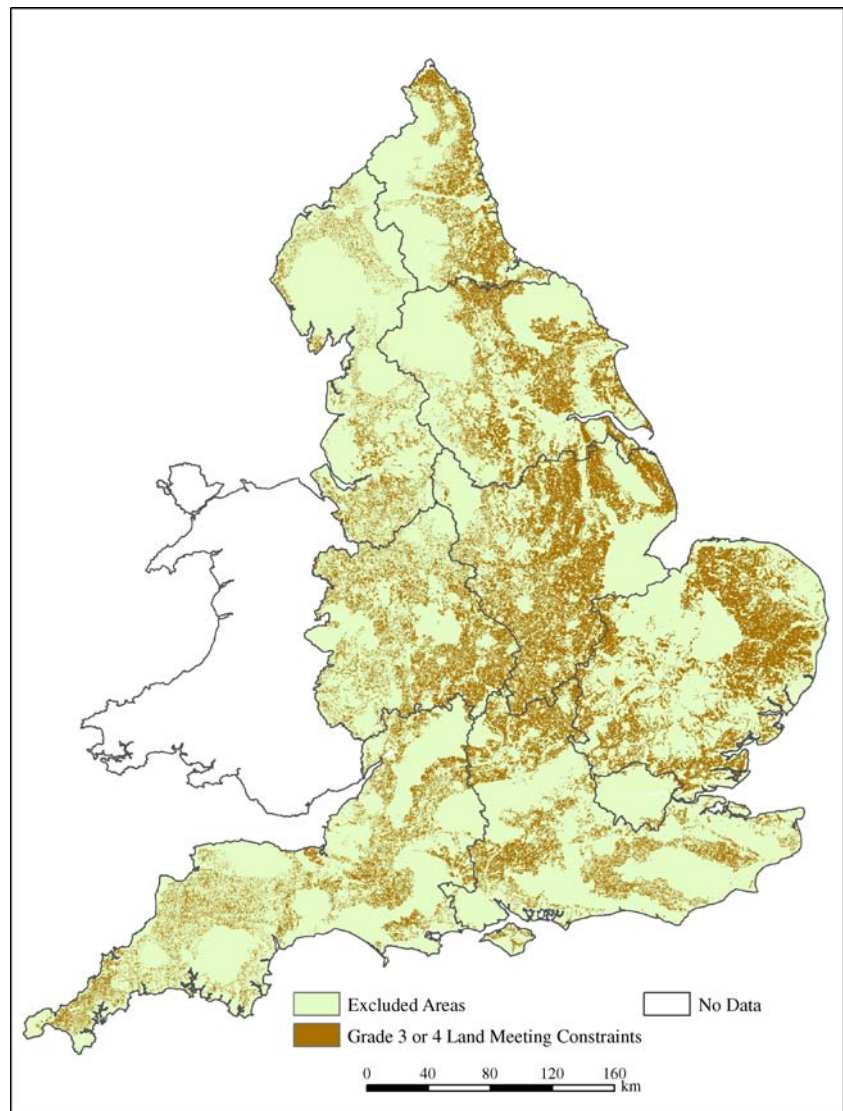
region, or in carbon losses through initial cultivation. As such, it is likely that energy crops plantings in these areas could be very limited or even discouraged. Table 1 also shows the area covered by environmentally sensitive landscapes and improved grassland in each region of England and the impact of adding these as further exclusions layers in the analysis. These data (Table 1) show that there are substantial areas of sensitive landscapes and improved grassland in certain regions (e.g. the North West, South West and South East). In total, when all such areas are excluded across England, together with the other nine absolute factors, the total suitable available area for planting is reduced by over 3 M ha to about 4.72 M ha (36.2% of England). However, there is considerable regional variation in the impact, with a reduction in the remaining suitable land ranging from 15% (East of England) to over 60% (North West and South West).

The totals above include all land types but planting of *Miscanthus* in the UK under the ECS has tended to avoid prime agricultural areas (i.e. ALC Grades 1 and 2) or the very poorest quality land (i.e. ALC Grade 5). Consequently, the analysis was refined to only include Grade 3 or 4 land. The total area of suitable land remaining after exclusion based on factors 1–9 that was also of Grade 3 or Grade 4 ALC was 5.68 M ha (43.6% of England). When all 11 factors are considered the total is reduced further to 3.12 M ha (23.9% of England). The map of the remaining suitable land after all 11 layers and ALC 3 and 4 restrictions are included in the analysis is shown in Fig. 2. The map highlights some of the spatial variability within and between regions, with many of the larger exclusion zones corresponding to major urban centres, areas of landscape

Table 1 Areas of land available (10^3 ha) for bioenergy plantings meeting primary and secondary, (sensitive landscapes, improved grassland) constraints and agro-economic preference (ALC Grade 3, 4) differentiated by region

Region	Total area of England	Available land 9 constraints	Total area of sensitive landscapes	Total area of improved grassland	Available land 11 constraints	Available land within ALC		Percent reduction by	
						Grade 3	Grade 4	Primary constraints (of total)	Secondary constraints (of available)
East Midlands	1,563.1	1,153.1	144.3	256.9	902.7	576.1	37.3	26.2	21.7
East of England	1,912.7	1,360.5	286.9	116.3	1,151.9	569.4	23.8	28.9	15.3
London	157.3	21.4	0.3	11.5	17.7	9.3	0.4	86.4	17.2
North East	859.0	383.7	254.2	189.7	235.6	18.1	24.3	55.3	38.6
North West	1,414.9	596.7	450.9	488.7	232.0	136.6	29.0	57.8	61.1
South East	1,907.9	1,138.0	733.4	415.1	538.8	316.6	81.9	40.4	52.7
South West	2,382.9	1,372.8	927.4	919.3	494.8	344.6	65.6	42.4	64.0
West Midlands	1,300.3	864.3	157.3	409.7	505.60	313.4	39.7	33.5	41.5
Yorks & Humber	1,541.4	880.1	413.9	274.9	640.6	336.3	35.1	42.9	27.2
England Total	13,039.5	7,770.6	3,368.6	3,082.1	4,719.8	2,783.0	337.2	40.4	39.3

Fig. 2 Land on ALC Grades 3 or 4 and outside the 11 planting constraints



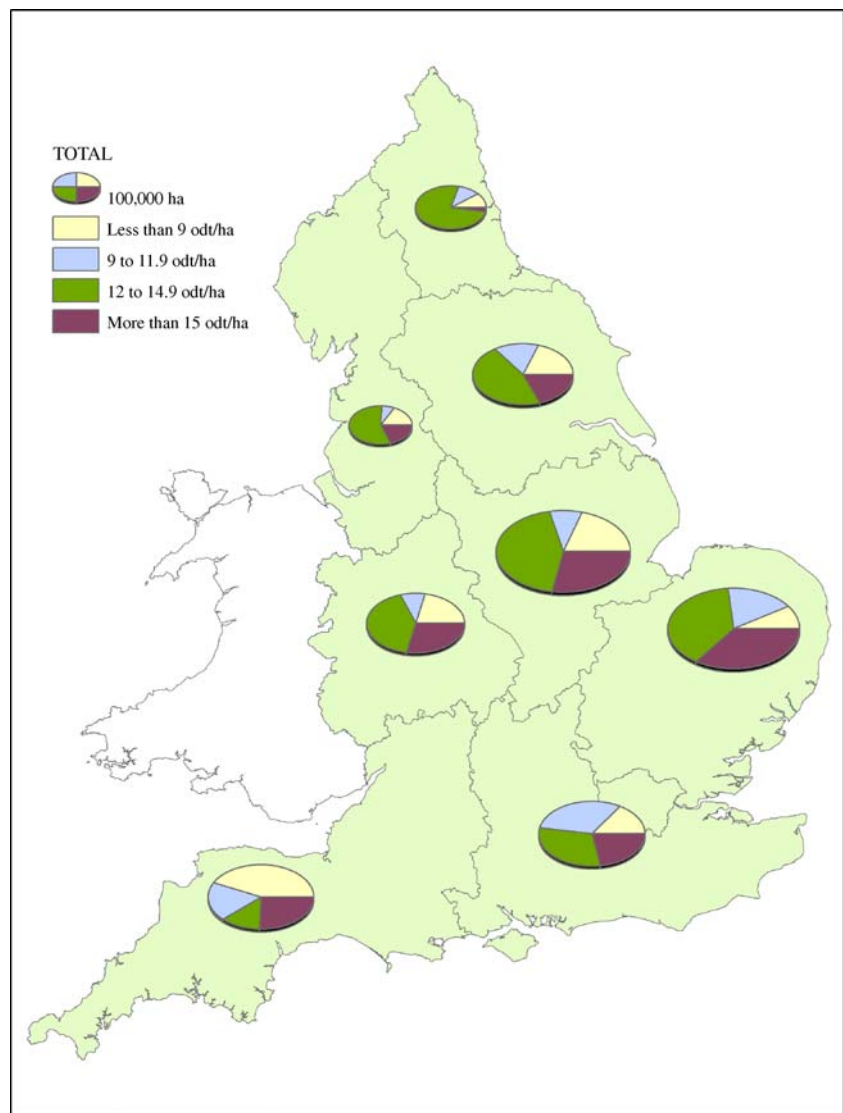
sensitivity and highest yielding areas which co-located with Grade 1 and 2 land.

Harvestable *Miscanthus* yield on all the suitable land remaining after only the first nine absolute factors were used as a mask, was calculated as 95.5 M odt, an average of 12.3 odt ha⁻¹. Only three regions (London, North East and North West) had a production potential of less than 10 M odt. When the calculation was restricted to Grade 3 or 4 agricultural land, the total yield across England was reduced to 67.6 M odt. Total harvestable yield on the suitable land (4.72 M ha) remaining after environmentally sensitive landscapes and grasslands were included in the analysis was calculated as 60.0 M odt, an average of 12.8 odt ha⁻¹. In the East Midlands and East of England production potentials were still above 10 M odt, and four other regions (South East, South West, West Midlands and Yorkshire & Humber) had totals above 5 M odt. When the calculation was further

restricted to using Grade 3 or 4 agricultural land only (3.12 M ha), then the total yield across England reduced to 38.9 M odt (an average of 12.5 odt ha⁻¹).

The pie charts in Fig. 3 show the regional distribution of the harvestable yield on this remaining land. For each region (London and South East have been combined) the size of the circle is proportional to the amount of remaining suitable available land, while the internal divisions of the pie show the extent of the land in each yield category. Some distinct contrasts in yield are apparent from the map with, for example, between 45% and 60% of land in the South East and South West having harvestable yields under 12 odt ha⁻¹ while in all other regions between 60% and 80% of available land had yields of more than 12 odt ha⁻¹. Nationally, about 36% of the land had yields under 12 odt ha⁻¹, 39% was in the range 12–14.9 odt ha⁻¹ and the remaining 25% yielded at least 15 odt ha⁻¹.

Fig. 3 Regional variations in harvestable Miscanthus yield for land on ALC Grades 3 or 4 and outside the 11 planting constraints



A key issue in the decision making about the expansion of biomass crops is what such planting might replace. To assess this, the distribution of the 3.12 M ha of suitable land shown in Fig. 2 (i.e. when all 11 factors and Grade 3 or 4 were included in the analysis) was compared with that of existing crops. The results of this exercise suggested that Miscanthus would occupy 63.4% of the arable cropping area in England and replace 60.2% of winter wheat and 63.9% of oilseed rape cultivation.

For the area of Miscanthus planting it is also possible to estimate the energy generation potential. Using a conversion efficiency of 32% [48] for a large-scale biomass plant [19] the total yield of 38.9 M odt translates to just over 55 M MWh of electricity which, using consumption figures from recent energy statistics [16, 17] is equivalent to the annual needs of around 12 million households or 20% of the total demand (industry/services/domestic) in 2005.

Miscanthus planting on the scale assessed above is far in excess of any current policy estimates, but the same approaches can be used to examine other scenarios. The Biomass Strategy [18] has a target of 350,000 ha of perennial energy crops in the UK so a similar amount of land was identified by starting from the total suitable land available after all 11 layers and ALC restrictions had been applied (Fig. 2) and then selecting areas with a yield of at least 9 odt ha⁻¹ (i.e. as a threshold for viable production). Of this land, 248,865 ha was on Grade 4 and this was supplemented by adding Grade 3 land of progressively higher yields until a cumulative total of 350,000 ha was exceeded. A total area of 362,859 ha was accumulated from a yield threshold of 9.9 odt ha⁻¹ yielding 4.56 M odt at an average yield of 12.5 odt ha⁻¹. This equates to 11.6% of the available 3.12 M ha, which varies regionally between 4–28% (Fig. 4). In essence, this area meets the Biomass

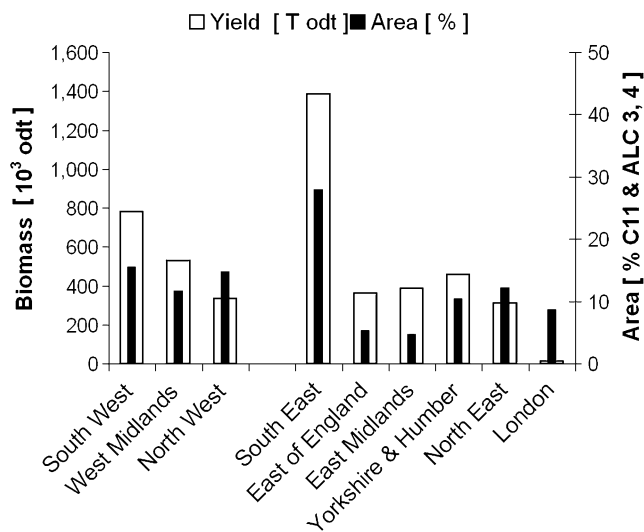


Fig. 4 Regional differences in the distribution of the Miscanthus production and its fractional area (%) of the fully constrained (C11) and most likely ALC-graded land applying a mapping approach to a 350,000 ha scenario

Strategy target, whilst respecting environmental constraints and yield considerations, on land that is not considered prime agricultural land.

When the distribution of the 362,859 ha was compared against the June Survey data, this land corresponded to 7.4% of the arable cropping area in England and was estimated as displacing 102,939 ha of winter wheat (5.5% of nationally planted area) and 26,799 ha of oilseed rape (5.9%). Using generation via large-scale biomass plants the total yield of 4.56 M odt translates to just over 6.5 M MWh of electricity which is equivalent to the annual needs of around 1.4 million households or about 2.4% of total demand (industry/services/domestic) in 2005. Note that the current UK strategy is for 12% electricity to be derived from all renewables (including biomass) by 2020.

The areas of wheat and oilseed rape displaced in the above scenario can be usefully compared with those corresponding to the surplus of UK exports for these two crops over imports. Using data from official statistics [14] these can be estimated at 97,222 ha for winter wheat and 68,710 ha for oilseed rape. This suggests that, under at least these assumptions, using the 350,000 ha for Miscanthus would not be a major problem for UK food security with respect to these two crops.

Discussion

The potential expansion of land under crops grown for energy production has raised considerable controversy of late. There are concerns over the impacts on food security and the environment, many of which have been examined at global,

and national scales, e.g. greenhouse gas emission [34, 43] and ground water recharge [24]. Using Miscanthus in England as a model, we present here a holistic method of examining the allocation of plantings which helps to identify possible conflicts between optimal allocation in terms of yield with the potential loss of alternative land use functions (such as nature and cultural heritage conservation). We focused on the scale that regional government operates in England and on identifying the alternate benefits (and associated opportunity costs) that may need to be chosen between in deciding whether to commit land to biomass cropping.

The results showed that the combined GIS-based yield and suitability mapping approach used here identified important differences in bioenergy generation potentials and pressures on land use at regional and finer spatial scales. These depend on more local characteristics and would be missed in analyses at national or higher levels.

Biophysical (e.g. soil, water, temperature), social (e.g. urban, and heritage sites) and environmental (e.g. nature, grassland, landscape character) data sets were integrated in the combined yield and suitability mapping exercise. Initially only (absolute) factors which would prevent planting of energy crops were included. These ranged from physical features, such as open water or steep slopes to environmental conditions such as designated areas of natural beauty, nature conservation or cultural heritage. When all of these data layers were included, the land area available for planting Miscanthus in the UK was reduced by about 40%. This varied considerable between regions, with more than 70% land suitable in East Midlands and East of England but only around 55% in the North-East and North-West. (Table 1)

At present in England, government guidance documents do not exclude biomass crops from being planted in environmentally sensitive landscapes and grasslands. However, there are other regulations and requirements that might restrict the use of such land for biomass. Adding these two further layers reduced the land available for biomass cropping in England to around 36% of the land area (Table 1). Again this varied between the regions, as might be expected. Certainly, tall grasses and bushes can change the appearance and perception of the landscape, which will also be influenced by topography (e.g. flat versus hilly) and the extent of other vegetation (e.g. hedgerows and trees), all of which vary regionally in the UK. Similarly, there are differences in the proportion of grassland found in different regions.

According to the June Agricultural Survey, if we take the area of land that was identified as suitable for Miscanthus after the nine absolute factors were included in the analysis (7.77 M ha), and subtract only the area of improved grassland (3.08 M ha), the remaining land area corresponds to the areas in England of arable crops, bare fallow, set-aside (0.2 M ha) and grassland under 5 years old (0.7 M ha).

The use of grassland older than 5 years, which has been in continuous decline since 1990, should also, perhaps, not be ruled out for biomass crops. Analysis of the pre-harvest GHG balance showed advantages of converting such grassland to *Miscanthus* [43], even without accounting for fossil fuel displacement. This analysis, did not, however, include application of N-fertilizer, which may become necessary on less fertile soil due to the annual export of nitrogen with the harvest [9]. Unfortunately, no experiments are available in *Miscanthus* to estimate carbon losses from planting and during establishment, or associated with the effect of different management practices, in former grassland sites. Ploughing up grassland could also result in very large losses of nitrogen as nitrate to waters and nitrous oxide to the atmosphere. We think that grassland older than 5 years should be considered a rather firm constraint until more is known about the potentially direct establishment of perennial energy crops in grassland using ways of minimum disturbance.

The *Miscanthus* yield map of the areas identified when all 11 layers were included in the suitability mapping showed a wide range of yield classes across the different regions. However, only 36% of land was estimated to yield less than the average 12 odt ha⁻¹ suggested in government documents [18] as the threshold for biomass production to be economical in the UK. These production guidelines were not based on harvestable yield, which would account for circa 25% biomass loss that occurs during the period in which the crop is left to dry on the stem [37]. The earlier estimates quoted, including the 12 odt above, referred to maximum yield and included also the non-harvestable pre-winter litter [35]. Therefore, even areas with at least 9 odt ha⁻¹ harvestable yield could be viewed as economically viable in England. In England, over two thirds of the ALC Grade 3 and 4 suitable land identified after layering all 11 factors into the analysis, gave yields that exceeded this threshold by 3 odt ha⁻¹. This suggests that, in England, biomass production, even on less valuable land, could be viable for around 80% of the possible cropable area under the current economic thresholds, provided the estimates of AWC using the PTF are reliable. Experimental data suggest that the PTF-based water availabilities are a better estimate than those data derived from the standard procedure of soil survey. The PTF can account for hydrological and physical differences, which quantify the high water availability in soils of low permeability. The PTF used here should be the most reliable as it was derived from a large number of soils of which 80 came from the UK [46].

It has been clearly recognised that restriction of biomass crops to land that is not the best land for food production is essential if food security is not to be exacerbated [23]. On what basis, however, is land for food production to be classified? Our analysis showed that allocation of *Miscan-*

thus to ALC Grades 3 or 4 only could still displace up to 60.2% of the land used for winter wheat and 63.9% for oilseed rape in England, albeit not necessarily the highest yielding land for these crops. If current surpluses for these two crops are factored in, achieving the 350,000 ha target proposed by government strategy to meet renewable obligations for power generation [18] would appear not to present a direct problem for domestic food production. This could easily be achieved in England by growing *Miscanthus* on ALC Grades 3 and 4, whilst still restricting planting to areas identified as suitable. The impact that the loss of surplus would have on food security globally is not something we have attempted to quantify. Here, we have focused on conflicts between energy production and other products and services the land could provide but the general method could also be useful in investigating economic trade-offs.

The power of the approach is that it can be used to investigate the potential impacts of a whole range of different scenarios of biomass crop expansion to highlight what the specific pressures on land use would be. We have explored only one under a set of assumptions as an example, which does not suggest a problem for domestic food production in the UK. However, if biomass production is to be increased beyond 350,000 ha, to the circa 1–2 million ha which may be required in the UK to meet current targets for renewable liquid transport fuels [18], there will be increased pressure on remaining land.

Our analysis raises several pertinent issues. In practise, a number of the absolute factors used, by their nature, completely preclude all possibility of planting biomass crops (e.g. 4. slope steepness; 6. major rivers; 7. lakes and 5. urban areas). If food production is not encroached on, increased pressure would, therefore, be placed on the rather few factors where there is some scope for planting provided there is a change in the current policy. Impacts on landscape sensitivity and increasing pressure to cultivate non-permanent grassland are likely to be manifested first but even designated or culturally significant areas may come under pressure. Alternatively, if the price of biomass feedstocks becomes competitive with grain prices there may even be conversion of ALC Grade 2 or Grade 1 land to biomass, thus increasing the competition with food production.

The results also indicate that different pressures will be exerted in different regions. In areas that are largely arable, such as the East Midlands, increasing land areas under biomass crops could place pressure on current food production unless some of the limited environmentally sensitive areas are utilised. In regions with less arable land, such as the South-West, increased biomass production is likely to place pressure on environmentally sensitive areas and other ecosystem functions of the land whilst use of high grade land would significantly effect food production in the region. Taking England as a whole it is possible that these

effects may even out, but impacts at regional levels are likely to be significant which should be recognised when national policy is drawn up. This illustrates how important it is to make yield and suitability mapping results freely available to farmers, policy-makers and interested stakeholders such as Nature, Heritage and Environmental interest groups.

The results here also emphasise the need for on-farm yield measurements and the importance of crop breeding programmes for second generation crops, which place emphasis on selecting genotypes that are able to sustain higher economic yields on non-prime land. Calculation of the carbon and GHG consequences of converting non-cultivated land into biomass crop plantations would also need to be taken into account but the approach outlined would help in this exercise by identifying the land areas affected under different scenarios. Considering the difference of yields and availability of land between West and East, the use of grassland could be an option but more research is needed on optimising planting and establishment methods (e.g. direct planting into grass) to avoid causing a flush of released C and N.

In summary, the GIS-based method described here provides an effective approach for identifying the land areas where biomass crops are most likely to be planted, the possible locations of expansions under different scenarios and the different conflicts that will inevitably need to be resolved when large-scale expansion occurs.

Acknowledgements This paper is the result of collaboration among members of two Research Council UK (RCUK) consortia projects: The constraints mapping is part of the RELU-Biomass project (<http://www.relu-biomass.org.uk>) funded under the Rural Economy and Land Use programme of the ESRC, BBSRC and NERC and the yield mapping is part of the TSEC-BIOSYS project (<http://www.tsec-biosys.ac.uk/>) funded by NERC. We are grateful to Natural England for providing details of approved Energy Crop Scheme agreements. Rothamsted Research is and Institute of the BBSRC.

References

- Adler PR, Del Grosso SJ, Parton WJ (2007) Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. *Ecol Appl* 17(3):675–691
- Aylott MJ, Casella E, Tubby I, Street NR, Smith P, Taylor G (2008) Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. *New Phytologist*. doi:10.1111/j.1469-8137.2008.02396.x
- Berry JK (1993) Cartographic modeling: the analytical capabilities of GIS. In: Goodchild MF, Parks BO, Steyaert LT (eds) *Environmental modeling with GIS*. Oxford University Press, Oxford, pp 58–74
- Boorman, DB, Hollis JM, Lilly A (1995) In *Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom*. Report No. 126, CEH, Wallingford
- Campbell JE, Lobell DB, Genova RC, Field CB (2008) The global potential of bioenergy on abandoned agriculture lands. *Environ Sci Technol*. doi:10.1021/es800052w.CCC
- Capener P, Scholes H, Ward S, Evans N (2004) REvision 2010—Establishing county/sub regional targets for renewable electricity development to 2010: In: Capener P, Consultants B (ed) Report to the government office for the South West and the South West Regional Assembly
- CEH, Centre for Ecology & Hydrology (2008) Land Cover Map 2000. http://www.ceh.ac.uk/sections/seo/lcm2000_home.html. Cited 15 Dec 2008
- Centre for Sustainable Energy (2007) Devon Miscanthus and woodfuels opportunities statement. In: Centre for Sustainable Energy B (ed) Report to Devon Wildlife Trust
- Christian DG, Poulton PR, Riche AB, Yates NE, Todd AD (2006) The recovery over several seasons of N-15-labelled fertilizer applied to *Miscanthus x giganteus* ranging from 1 to 3 years old. *Biomass Bioenergy* 30(1):125–133
- Clifton-Brown JC, Stampfl PF, Jones MB (2004) Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Glob Chang Biol* 10(4):509–518
- Crosbie T (2008) Why corn will remain the primary ethanol feedstock for the next ten years in the US? Presentation given at the Biobased Industry Outlook Conference, 8 SEPT. Iowa State University, Ames, Iowa
- DEFRA Department for Environment, Food and Rural Affairs (2003) <http://www.defra.gov.uk/farm/singlepay/furtherinfo/crosscomply/index.htm>
- DEFRA, Department for Environment, Food and Rural Affairs (2007) Opportunities and optimum sitings for energy crops. <http://www.defra.gov.uk/farm/crops/industrial/energy/opportunities/index.htm>. Cited 15 Dec 2008
- DEFRA, Department of Agriculture and Rural Development (Northern Ireland), Welsh Assembly Government and Scottish Government (2007) *Agriculture in the United Kingdom 2007*. Defra, London, pp 31–37
- DEFRA, Department for Environment, Food and Rural Affairs (2008) *Agricultural Land Classification*. <http://www.defra.gov.uk/rds/lgmt/ALC.htm>. Cited 15 Dec 2008
- Department for Business, Enterprise and Regulatory Reform (2007a) *Digest of UK Energy Statistics 2007*, TSO, London, 2007
- Department for Business, Enterprise and Regulatory Reform (2007b) *Regional and local electricity consumption statistics for 2006*, Energy Trends, URN 07/79d, pp 21–29, BERR Publications, London, December 2007
- DTI, Department of Trade and Industry, Department of Transport and Department (DFT) and Department for Environment, Food and Rural Affairs (DEFRA). (2007) *UK Biomass Strategy*
- Dornburg V, Faaij APC (2001) Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. *Biomass Bioenergy* 21(1):91–108
- EDINA, University of Edinburgh (2008) Maps & data. <http://edina.ac.uk/maps/>. Cited 15 Dec 2008
- English Heritage (2006) *Biomass energy and the historic environment*. <http://www.helm.org.uk/upload/pdf/Biomass-Energy.pdf>. Cited 15 Dec 2008
- ESRI, Environmental Systems Research Institute (2008) Desktop GIS. <http://www.esri.com/products/index.html>. Cited 15 Dec 2008
- Field CB, Campbell JE, Lobell DB (2007) Biomass energy: the scale of the potential resource. *Trends Ecol Evol* 23(2):65–72
- Finch JW, Hall RL, Rosier PTW, Clark DB, Stratford C, Davies HN, Marsh TJ, Roberts JM, Riche AB, Christian DG (2004) The hydrological impacts of energy crop production in the UK. In: *Final Report to ETSU*. CEH, Wallingford
- Forestry Commission (2008) National inventory of woodland and trees. <http://www.forestry.gov.uk/forestry/HCOU-54PG4D>. Cited 15 Dec 2008

26. Gallagher E (2008) Review of the indirect effects of biofuels. Renewable Fuels Agency. http://www.dft.gov.uk/rfa/reportsand_publications/reviewoftheindirecteffectsofbiofuels/executivesummary.cfm
27. Karp A, Shield I (2008) Bioenergy from plants and the sustainable yield challenge. *New Phytol* 179(1):15–32
28. MAGIC, Multi-Agency Geographic Information for the Countryside (2008) Dataset information and download facility. <http://www.magic.gov.uk/DataDoc/datadoc.asp>. Cited 15 Dec 2008
29. National Corn Growers Association (2006) How much ethanol can come from corn? Available at: <http://www.ncga.com/ethanol/pdfs/2006/HowMuchEthanolCan%20ComeFromCorn.v.2.pdf>. Verified 19 SEPT 2008
30. Natural England (2008a) Energy Crops Scheme. <http://www.naturalengland.org.uk/planning/grants-funding/energy-crops/default.htm>. Cited 15 Dec 2008
31. Natural England (2008b) GIS digital boundary datasets. http://www.english-nature.org.uk/pubs/gis/gis_register.asp. Cited 15 Dec 2008
32. Neukirchen D, Himken M, Lammel J, Czyionka-Krause U, Olf HW (1999) Spatial and temporal distribution of the root system and root nutrient content of an established *Miscanthus* crop. *Eur J Agron* 11:301–309
33. NSRI, National Soil Resources Institute (2008) LandIS—Land information system, <http://www.landis.org.uk/gateway/ooi/welcome.cfm>. Cited 15 Dec 2008
34. Powlson DS, Riche AB, Shield I (2005) Biofuels and other approaches for decreasing fossil fuel emissions from agriculture. *Ann Appl Biol* 146:193–201
35. Price L, Bullard M, Lyons H, Anthony S, Nixon P (2004) Identifying the yield potential of *Miscanthus x giganteus*: an assessment of the spatial and temporal variability of *M. x giganteus* biomass productivity across England and Wales. *Biomass Bioenergy* 26(1):3–13
36. Rafaschieri A, Rapaccini M, Manfrida G (1999) Life Cycle Assessment of electricity production from poplar energy crops compared with conventional fossil fuels. *Energy Convers Manage* 40(14):1477–1493
37. Richter GM, Riche AB, Dailey AG, Gezan SA, Powlson DS (2008) Is UK biofuel supply from *Miscanthus* water-limited? *Soil Use Manage* 24:235–245
38. Robinson RA, Sutherland WJ (2002) Post-war changes in arable farming and biodiversity in Great Britain. *J Appl Ecol* 39:157–176
39. Rowe RL, Street NR, Taylor G (2009) Identifying potential environmental impacts of large-scale deployment of bioenergy crops in the UK. *Renew Sustain Energy Rev* 13:271–290
40. Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319(5886):1238–1240
41. Seeruttun S, Crossley CP (1997) Use of digital terrain modelling for farm planning for mechanical harvest of sugar cane in Mauritius. *Comput Electron Agric* 18(1):29–42
42. Sherrington C, Bartley J, Moran D (2008) Farm level constraints on the domestic supply of perennial energy crops in the UK. *Energy Policy* 36:2504–2512
43. St. Clair S, Hillier J, Smith P (2008) Estimating the pre-harvest greenhouse gas cost of energy crop production. *Biomass Bioenergy* 32(5):442–452
44. The Royal Society (2008) Sustainable biofuels: prospects and challenges. The Royal Society, London
45. von Blottnitz H, Cu, rra n MA (2007) A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *J Cleaner Prod* 15(7):607–619
46. Woesten JHM, Lilly A, Nemes A, Le Bas C (1999) Development and use of a database of hydraulic properties of European soils. *Geoderma* 90(3–4):169–185
47. WorldClim (2008) WorldClim version 1.4. <http://www.worldclim.org>. Cited 15 Dec 2008
48. Yang YB, Newman R, Sharifi V, Swithenbank J, Ariss J (2007) Mathematical modelling of straw combustion in a 38 MWe power plant furnace and effect of operating conditions. *Fuel* 86:129–142