Global Change Biology (2007) **13**, 2283–2295, doi: 10.1111/j.1365-2486.2007.01419.x

European-wide GIS-based modelling system for quantifying the feedstock from *Miscanthus* and the potential contribution to renewable energy targets

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Abstract

Reliable estimates of feedstock resources are a prerequisite to the establishment of a biomass based-industry for energy and non food products. Field trials in the European Union (EU) show that *Miscanthus* spp. can produce high yields. Here we use a model (MISCANMOD) coupled with a GIS environment to estimate the contribution that *Miscanthus* could make to projected national electricity consumption. We describe the integration of different data sets, transformation procedures, and spatial analyses using GIS to produce energy statistics for the EU-25. Overall, *Miscanthus* grown on the 10% of arable land which is currently in set-aside could generate 282 TWh yr^{-1} electricity. This would meet 39% of the EU-25 target of 723 TWh yr^{-1} of electricity from renewable energy sources (RES) by 2010. As RES targets rise, land available for energy crops is also expected to increase. We consider three additional scenarios where *Miscanthus* could be grown on 10%, 20% and 35% of all agricultural land and we estimate it could generate respectively 345, 691 and 1209 TWh yr^{-1} of electrical energy. At a national scale France, Poland and Germany have the highest potentials for *Miscanthus* production based on agricultural land area (respectively 83, 52, 49 TWh yr^{-1} when 10% agricultural land is used). Finally, we reduced the scale to the EU NUTS2 (Nomenclature of Territorial Units for Statistics) regions to examine regional generation capacities. Key regions have been identified where national RES targets are exceeded. These regions could become net exporters of renewable energy.

Keywords: biomass, GIS, MISCANMOD, *Miscanthus*, model, Nomenclature of Territorial Units For Statistics (NUTS), Renewable Energy Sources (RES)

Received 20 September 2006; revised version received and accepted 19 March 2007

Introduction

The European target of 12% contribution from renewable energy sources (RES) to gross inland energy consumption by 2010 (European-Commission, 2004a) is ambitious for most European Union (EU)-15 countries. Biomass crops will form a major part of the renewable energy mix (Olesen *et al.*, 2005) and the accession of another 10 member states to make up the EU-25 in 2004 has increased the land resources potentially available for energy crops by 30%. The current European commission estimates (EEA, 2005) suggest that biomass will make a contribution of 130 Mtoe (1512 TWh yr^{-1}), and perennial rhizomatous grasses such as *Miscanthus* could contribute a large proportion of this. In order to reliably quantify this, it is necessary to make spatial analyses of biomass yield based on models, which can exploit existing data sources. A conservative estimate of land resources available for energy crops assumes that the current set-aside of arable land, which is set to 10% for the period 2001–2006 by the European Commission (Zervondaki, 1999) is used for biomass production. However, recent economic projections for land resources in the EU-25 available for energy crops have shown that larger areas will become available, rising from 17% of agricultural land in 2010 to 33% of agricultural land in 2020 (Thrän *et al.*, 2006).

Here, we have used four scenarios for available land and made projections of the contribution of *Miscanthus* biomass to national electricity consumption. In the first

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scenario, we have used current set-aside levels (10%) of arable land made available to *Miscanthus*. In the second scenario, we assume 10% of the agricultural land (arable plus pasture land) is used for *Miscanthus* crops. This is similar to the scenario that we used previously (Clifton-Brown *et al*., 2004) for the EU-15, but we have now extended the calculation to include the EU-25. The third and fourth scenarios, are derivatives of the second scenario, where the impact of increasing land resources to 20% and 35% of the agricultural land are explored. The justification for such large areas devoted to an energy crop like *Miscanthus* is based on the economic projections for energy prices and the decline in areas needed to sustain adequate food supply. Although the European Commission has produced a number of alternative energy scenarios (European-Commission, 2004b) calculations in this paper are all based on the '12% renewables share in 2010' case outlined by the European Commission (2004) in the report 'Scenarios on key drivers'.

The significant advance of this work on Clifton-Brown *et al*. (2004) lies in the use of land use scenarios within a GIS to perform spatial analyses of the contribution of *Miscanthus* to energy crop resources in the EU-25. The prediction of *Miscanthus* productivity was done with an updated MISCANMOD growth model (Clifton-Brown & Lewandowski, 2000), which is a MS EXCEL spreadsheet model that uses a MACRO in Visual Basic. GIS is the appropriate tool for such spatial analysis questions, but there is often a lack of the high quality datasets which fit the exact data requirements for yield modelling. The objectives of this paper were twofold: (i) to describe the necessary transformation methods applied for creating a consistent GIS database and (ii) to perform spatial analyses for predicting *Miscanthus* biomass resources and their contribution to RES targets under four land resource scenarios on national and regional (NUTS2, Nomenclature of Territorial Units for Statistics) levels across EU-25.

Materials and methods

Software

In this study most dataset transformations and spatial analyses were made using ArcGIS™, Version 9.0, Environmental Research Institute (ESRI® Inc.), along with ArcGIS™ Spatial Analyst, and ArcGIS™ Geostatistical Analyst. Some operations were carried out with the raster based GIS software package IDRISI 32 (Version I32.20, Clark Labs).

Data matrix and spatial data bases

Information on source datasets was summarized in a data matrix describing characteristics such as geographic region covered, file format, spatial data structure, scale or resolution, spatial reference system and projection, storage medium, time of creation or period covered, charges and terms of use (Table 1). The Data Matrix was an invaluable tool for comparing the different datasets available and was used to decide which were used in modelling and which were used as independent quality controls. The four source datasets used for spatial analysis are described in turn.

(1) The gridded climate dataset Climate Research Unit (CRU) CL 1.0 is part of the climatologic database maintained by University of East Anglia, UK (Hulme *et al*., 1995). It contains meteorological data for each 0.5° latitude by 0.5° longitude grid square between 31°75′W; 25°25′N and 65°75′E; 80°75′N, including average monthly values for air temperature (°C), precipitation (mm), and sunshine hours (h), calculated from a 30 year period (1961–1990) of measurements, corrected for the mean altitude within each grid square that covers land. Sunshine hours were converted to incident radiation (MJ $m^{-2}\,day^{-1}$) and were supplied by Dr Mark New (Department of Geography, Oxford University).
(2) The Pan-European Land Cover Monitoring (PELCOM) land cover raster grid dataset is the main product of the PELCOM Project, which was carried out to create a consistent pan-European land cover database (www.geo-informatie.nl/projects/pelcom/public/index.htm). Based on NOAA-AVHRR satellite data and ancillary information the discrete raster grid, with a cell size of 1.1 km, classifies European land cover into 16 land use classes.
(3) The European soil map is part of the United Nations Food and Agriculture Organization (FAO) Soil Map of the World and derived soil properties database (FAO, 1995). At a scale of 1 : 5 000 000 the digital map represents coded soil mapping units across Europe. The plant available water (PAW) capacity grid surface is one of several spatial soil datasets contained on the Global Soil Data Products CD-ROM (www.daac.ornl.gov/SOILS/igbp.html) compiled by the Global Soil Data Task of the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) Potsdam, Germany. We derived from the FAO Soil Map of the World database a point grid layer with a $0.5 \times 0.5°$ resolution relating major classes of global soils to PAW.
(4) The European Countries, Provinces, and Regional Demographics polygon layers, outlining political boundaries and different administrative levels of the European countries is part of the European Basemap dataset, which is contained on CD 1 of the ESRI® (www.esri.com) Data & Maps Media Kit 2000.

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Table 1 Summary of the main characteristics of the datasets used for the model.

Information	Dataset and reference	Geographic region	File format	Projection	Scale/resolution	Data source	Period covered
Climate							
Temperature (°C), rainfall (mm), Sunshine (H)	CRU CL.1.0 Hulme *et al.* (1995)						
Radiation ($MJ\,m^{-2}\,day^{-1}$)	Derived from CRU Sunshine H, Mark New (personal communication)	Europe	ASCII Tab delimitated text file	Latitude/ longitude	$0.5° \times 0.5°$	www.cru.uea.ac.uk	1960–1990
Potential evaporation ($mm\,day^{-1}$)	Derived from CRU, Nigel Arnell (personal communication)						
Soil							
Soil map Europe	Digital soil map of the world, FAO (1995)	Europe	ARC/INFO Export vector files	Geographic projection	1 : 5 000 000	www.fao.org	1995
Plant Available Water (PAW)	Global Soil Data Products (IGBP-DIS)	Global	Idrisi (*.img)	Geographic projection spherical datum	$5' \times 5'$ (arc-minutes)	www.daac.ornl.gov	2000
Landcover							
Landcover Europe	Pan-European Land COver Monitoring (PELCOM)	Europe	ARC/INFO export grid	Albers conical equal area WGS72	1100 m × 1100 m	www.geo-informatie.nl	2000
Administrative boundaries							
European Countries							
European Provinces	ESRI Data & Maps 2000	Europe	Shapefile (*.shp)	Geographic projection datum: D_WGS_1984	n/a	www.esri.com	2000
Regional Demographics							

CRU, Climate Research Unit; FAO, Food and Agriculture Organization; IGBP-DIS, International Geosphere-Biosphere Programme Data and Information System; WGS, World Geodetic System.

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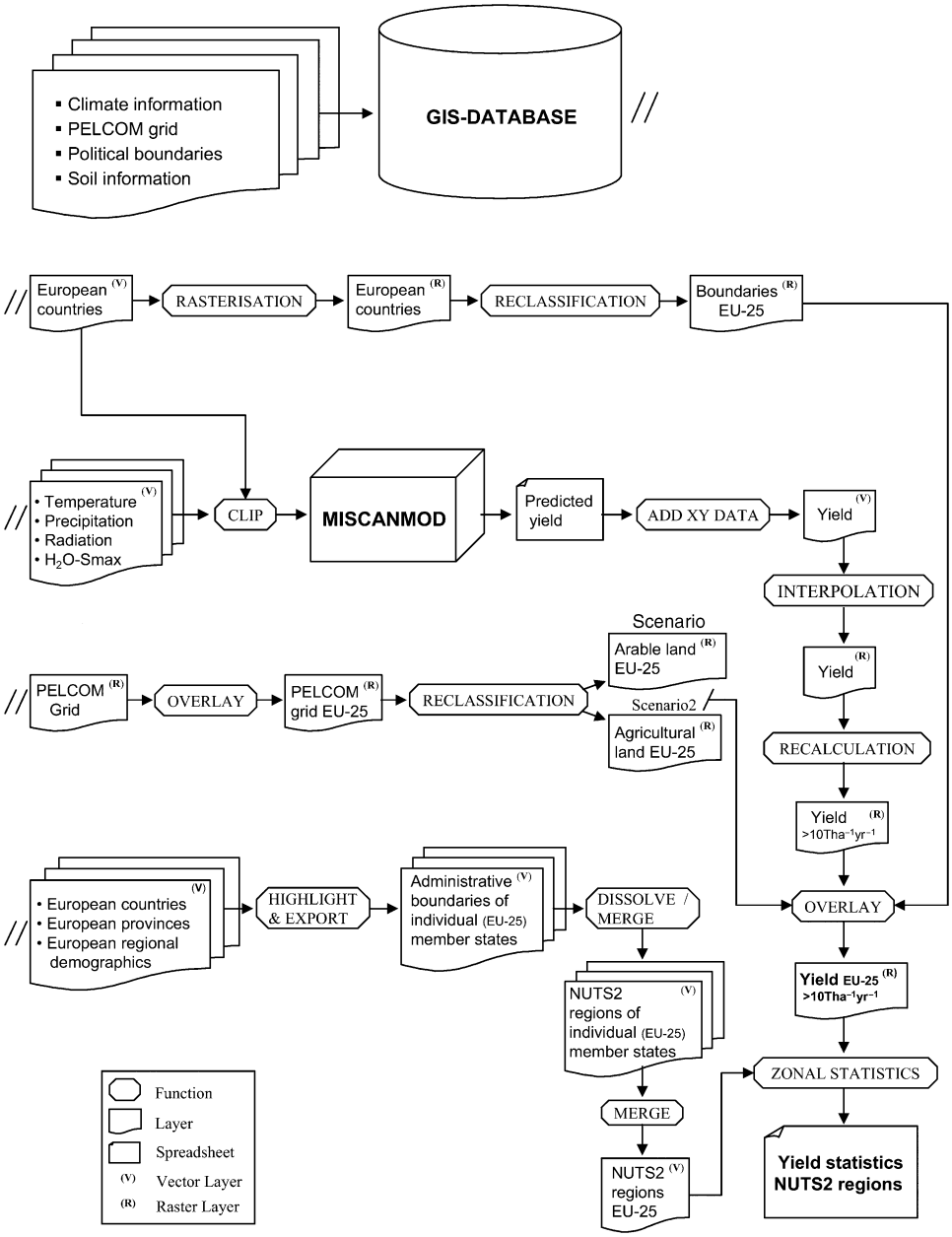

Fig. 1 Conceptual model of data flow and spatial modelling algorithms applied.

Database creation

With datasets originating from different sources and being diverse in context of their computational application, the majority of source datasets (Table 1) utilised were (i) encoded in different file formats, (ii) referenced to diverse coordinate systems, and (iii) showed different geographical coverage, geographic scale and resolution. In order to be able to analyse and compare the different map layers meaningfully and to guarantee a consistent database we (i) converted all source datasets into a file format supported in ArcGIS™, (ii) re-projected all geospatial layers to a common frame of reference, (iii) set a common map origin, (iv) defined an analysis extent and (v) adopted a consistent map resolution. The NUTS2 regions were not available as geospatial layer and had to be produced by manipulating and integrating the borders of different administrative levels represented in the European Countries, European Provinces, and European Regional Demographics datasets.

ArcGIS™ is capable of managing vector and raster data models (Booth & Mitchell, 2001). However, as the

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raster model offered superior computational efficiency and allowed sophisticated data manipulation we carried out most spatial modelling and data analysis using raster data structures. Before any advanced spatial analysis some exploratory data analysis was performed. This included (i) a thorough visual inspection of created map layers using different display capabilities (zoom, highlight, symbology, classes), (ii) the studying of layer properties, which are customarily compiled and displayed by ArcGIS™, and (iii) the creation and evaluation of statistical dataset information such as frequency distribution and summary statistics. All datasets were converted to the European Spatial Reference System (ETRS89) using a specified Lambert Azimuthal Equal Area Projection (False Easting: 4 321 000, False Northing: 3 210 000, Central Meridian: 10 Latitude of Origin: 52). The grid origin was set to 1 700 000 m west and 180 000 m south of the projection centre point (52°N, 10°E), the analysis extent to 3 900 000 m east and 4 010 000 m north, thus covering the area of the European Member States (EU-25) except the overseas protectorates and some offshore islands. Due to the spatial resolution of the source data, with cell sizes ranging from 1.1 km^2 (PELCOM grid) up to approximately 50 km^2 (meteorological data) it was necessary, but also valid from an analytical and modelling perspective, to adopt a two-tiered approach. All interpolation procedures and intermediate processing of derived layers was carried out with a cell size of 20 km × 20 km. Any adoption of a smaller grid size (higher resolution), would not have revealed any additional information nor would it have been more accurate. All other data analysis procedures, together with the concluding layer synthesis and generation of the final map was completed with a grid size of 1.1 km × 1.1 km (corresponding to PELCOM grid). The adoption of the smaller grid size does not change the underlying resolution of 20 km × 20 km but allows a close cut of the yield layer with the administrative boundaries resulting in more accurate area calculations.

Conceptual model and metadata

A description of the model components in the form of flow diagrams was used to keep a synoptic overview of model development. Point estimates of yield and spatial modelling were performed in steps and involved linking several processes and sub models (Fig. 1). Each process included input data, an algorithm applied to transform the data, and the resulting output data. Using the templates offered by ArcGIS (Vienneau and Bailey, 2001) we adopted the United States Federal Geographic Data Committee's (FGDC) Content Standard (www.fgdc.er.usgs.gov) and created individual metadata files for each data layer produced that is maintained within the project environmental database.

MISCANMOD

MISCANMOD is a spreadsheet model developed for the prediction of above-ground biomass production from *Miscanthus* (Clifton-Brown *et al*., 2004). In brief, it is a physiologically based production model where radiation interception and radiation use efficiency (Monteith, 1977) are specifically parameterized for *M. x giganteus* (Clifton-Brown & Lewandowski, 2000). To run MISCANMOD a moderate number of crop-specific parameters are combined with climate and soil data. We used monthly values of European climate data on a 0.5 × 0.5° grid (Table 1) but for model simulations these monthly values were linearly interpolated to produce daily values to drive crop processes determining yield on a daily time step. Peak autumn yield is assumed to occur when the mean air temperature falls below 10 °C as crop growth virtually stops at this point (Clifton-Brown & Jones, 1997). We assumed in this study that peak autumn yields above 10 t DM $ha^{-1} yr^{-1}$ were economically viable (depending on many factors including oil price, land price and availability of appropriate machinery). Delaying harvest time until spring results in reduced nutrient and moisture contents, thus increasing biomass quality (Lewandowski *et al*. 2003). However, delayed harvest time also leads to significant reduction in the harvestable yield (Jørgensen, 1997). Reanalysis of data presented in Lewandowski *et al*. (2003), showed that the average yield loss for *M. x giganteus* at five latitudinally distributed sites throughout Europe was 33% of peak yield. We applied this 33% reduction universally to estimate the harvestable yield.

Spatial analysis

GIS was used for detecting patterns and irregularities in map layers and for processing 'raw' geographic data into new functional information. Spatial units used for the model are the EU-25, the individual EU member states and NUTS 2 regions, which represent the second of the five levels of administrative classification of the EU as defined by EUROSTAT, (www.epp.eurostat.ec.europa.eu) the Statistical Office of the EU.

Estimated peak autumn yield derived from MISCANMOD and available in the form of a point layer with regular- spaced sample locations across Europe (0.5 × 0.5° grid), were interpolated to produce spatially continuous yield values across Europe. Various interpolation methods (inverse distance weighting, local polynomial interpolation, ordinary kriging and simple kriging) were tested. Based on a visual and statistical assessment (aver-

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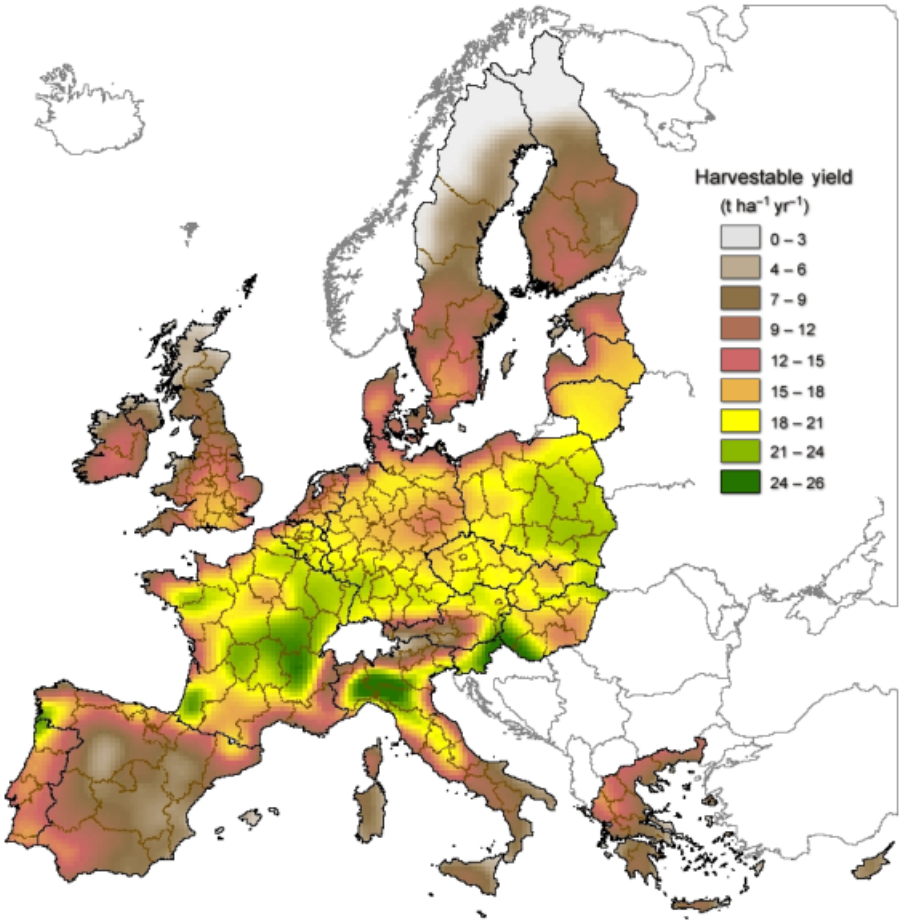

Fig. 2 Predicted harvestable *Miscanthus* yield (t DM ha^{-1}) showing national and regional boundaries (NUTS2) in EU-25 based on yield estimates interpolated from $0.5 \times 0.5^{\circ}$ climate and soil grids.

age standard error, standardized mean, root mean square prediction error, standard root mean square prediction error) ordinary kriging (K-Bessel semivariogram model, variable search radius, five neighbours) was selected as the method to generate a grid surface representing peak autumn *Miscanthus* yield across Europe.

Overlay analysis and zonal statistics

Any grid cells of the yield surface that did not (i) represent peak yield values equal or higher than 10 t DM ha^{-1} yr^{-1}, (ii) coincide spatially with an area that is classified as rainfed arable land (scenario 1) and grassland or rainfed arable (scenario 2) and (iii) belong geographically to the area covered by the EU-25, were excluded.

To integrate these criteria into the model it was necessary to generate a set of overlay 'mask' layers from the corresponding raster layers (PELCOM grid, yield surface, European country raster). The product of the three masks and the interpolated yield surface resulted in a yield surface on which the EU, national and NUTS2 borders were applied to calculate zonal statistics (McCoy & Johnston, 2001) for the area and yield statistics (number of grid cells, area covered, minimum, maximum, average-, and total yield) for the three adopted administrative levels.

Results

Model estimates of European wide yield

In this study only rainfed peak yields above 10 t DM ha^{-1} yr^{-1} are considered to be economically viable. This threshold is lower than those in earlier economic studies (Heath *et al.*, 1994 ; Bullard, 2001), but we believe is appropriate because of current rises in energy prices. Applying this cut off threshold Cyprus (CY00) and Malta (MT00) along with a further 16 NUTS2 regions were excluded from further calculations.

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Table 2 Scenarios considered and their impact on the share of RES demand and gross electricity consumption in the EU-25

Scenario no.	1	2	3	4
Land resources	10% arable*	10% agricultural†	20% agricultural†	35% agricultural†
Area of available land (ha $\times 10^6$)	13	16	32	56
Achievable biomass (t $\times 10^6$ yr^{-1})‡	193	237	474	829
Electricity generation (TWh yr^{-1})§	282	345	691	1209

Year	EU-25 RES demand¶ (TWh yr^{-1})	% share of *Miscanthus* on EU-25 RES demand			
2000	1118	25	31	62	108
2010	2410	12	14	29	50
2020	2730	10	13	25	44
2030	2937	10	12	24	41

Year	EU-25 gross electricity consumption¶ (TWh yr^{-1})	% share of *Miscanthus* on EU-25 gross electricity consumption			
2000	2922	10	12	24	41
2010	3444	8	10	20	35
2020	3973	7	9	17	30
2030	4425	6	8	16	27

*Equivalent to EU set aside.
†Agricultural land = arable + grassland.
‡Achievable biomass is the product of suitable land area and peak autumn yield above 10 t DM ha^{-1} yr^{-1} minus 33% reduction for losses due to delayed harvest.
§Electricity generation based on assumed energy content of 15 GJ t^{-1}, and a combustion conversion efficiency of 35%.
¶European-Commission (2004b) European Energy and Transport Scenarios on Key Drivers.
RES, renewable energy sources.

The distribution of modelled harvestable *Miscanthus* yield (peak autumn yield minus 33%) based on mean climate data across the EU-25 is shown in Fig. 2. Estimated yields range from 0 to 25.8 t ha^{-1} yr^{-1}. Highest yields (>23 t ha^{-1} yr^{-1}) are found in the plain regions south and east of the Alps (FR71, ITC1, ITC4, ITD5, HU22, HU23, and SL00). Lowest yields are found in areas of (1) high altitudes, and (2) high and low latitudes where temperature or water are limiting.

Available land resources

Based on the landcover classification of the PELCOM grid the land resources available within the EU-25 for scenario 1 (10% arable land) are 12.7 $\times 10^6$ ha. Extending the area to 10%, 20%, and 35% of agricultural land (arable plus grassland), as defined in scenario 2, 3, and 4 increased the land resources for the cultivation of *Miscanthus* across EU-25 by 26% (3.4 $\times 10^6$ ha), 153% (19.5 $\times 10^6$ hectare), and 342% (43.6 $\times 10^6$ ha), respectively. On a national or regional scale the share of grassland influenced the additional area available for cultivation of *Miscanthus*. The areas with most significant percentage gains are located in Republic of Ireland (2432%), Finland (526%), and Luxemburg (467%).

Electricity offset and contribution to RES

Calculated electricity offsets for *Miscanthus* production assumed a conversion factor of 15GJ of dry biomass (Hall & Scurlock, 1993), as well as a share of 35% of the energy available for production of electricity after combustion (Cannell, 2003). These figures are reasonably conservative to allow for loses in transmission, which are not calculated separately.

Energy demand projections presented in 5- year intervals from 1990 to 2030 by the European Commission in its report 'Scenarios on Key drivers' (European-Commission, 2004b) show strong growth in RES. The impact of the four land resource scenarios on the possible contributions of *Miscanthus* to growing RES demand and increasing gross electricity consumption in the EU-25 for the adopted '12% renewables share in 2010' scenario is shown in Table 2. The possible contribution of *Miscanthus* to the target of 21% share in

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Table 3 National production capacity of *Miscanthus* and its share in national RES targets set for 2010 for four land resource scenarios (see Table 2)

Country	Share (%) of RES in national gross electricity consumption	National RES targets in TWh yr^{-1}	Electricity production from *Miscanthus* (TWh) and its share (%) in national RES targets							
			Scenario 1		Scenario 2		Scenario 3		Scenario 4	
			TWh yr^{-1}	%	TWh yr^{-1}	%	TWh yr^{-1}	%	TWh yr^{-1}	%
Austria	78.1	54.8	5.7	10	6.1	11	12.2	22	21.3	39
Belgium	6.0	5.9	3.3	56	5.1	86	10.1	171	17.7	300
Cyprus	6.0	0.3	*	*	*	*	*	*	*	*
Czech Republic	8.0	5.9	12.5	213	12.6	215	25.1	430	44.0	752
Denmark	29.0	11.6	4.5	39	4.5	39	9.1	78	15.9	137
Estonia	5.1	0.4	3.1	706	3.2	719	6.4	1437	11.2	2515
Finland	31.5	29.2	0.79	3	4.9	17	9.7	33	17.0	58
France	21.0	119.3	61.2	51	83.0	70	165.9	139	290.4	243
Germany	12.5	77.1	42.3	55	48.9	63	97.9	127	171.3	222
Greece	20.1	15.2	2.6	17	3.7	24	7.4	48	12.9	85
Hungary	3.6	1.9	16.9	872	18.3	941	36.5	1882	63.9	3294
Irish Republic	13.2	4.4	0.24	6	6.6	150	13.1	300	23.0	526
Italy	25.0	88.2	20.9	24	23.2	26	46.4	53	81.3	92
Latvia	49.3	4.6	7.5	163	7.6	165	15.2	331	26.7	579
Lithuania	7.0	0.8	11.0	1297	11.4	1338	22.7	2676	39.8	4682
Luxembourg	5.7	0.5	0.08	17	0.5	96	0.9	191	1.6	335
Malta	5.0	0.1	*	*	*	*	*	*	*	*
Netherlands	9.0	12.1	2.7	22	5.2	43	10.4	86	18.1	150
Poland	7.5	13.3	49.6	374	51.5	388	103.0	776	180.2	1359
Portugal	39.0	22.5	4.8	21	5.4	24	10.8	48	18.9	84
Slovakia	31.0	11.0	5.1	46	5.7	51	11.3	103	19.8	180
Slovenia	33.6	4.7	1.7	37	1.8	39	3.6	77	6.4	135
Spain	29.4	89.6	9.0	10	11.7	13	23.4	26	40.9	46
Sweden	60.0	95.7	5.6	6	6.3	7	12.5	13	21.9	23
United Kingdom	10.0	45.3	10.9	24	18.5	41	37.0	82	64.8	143
EU-25	21.0	723	282	39	345	48	691	96	1209	167

*Cyprus and Malta have not been considered for electricity offset calculations because expected peak yield is below set threshold of 10 t ha^{-1} yr^{-1}.
RES, renewable energy sources.

gross electricity consumption (12% total energy consumption) from RES by 2010 are 282 TWh yr^{-1} for scenario 1 and 345 TWh yr^{-1} for scenario 2. This would meet 39% and 48% of the EU target of 723 TWh yr^{-1} electricity from RES by 2010 shown in Table 3. In 2030 the share of *Miscanthus* ranges between 10% and 41% contribution to RES demand and between 6% and 27% contribution to gross electricity consumption depending on the land resource scenario adopted.

Each EU member state has proposed its own national RES target for 2010 (European-Commission, 2004a). Targeted share of RES on gross electricity consumption ranges from 3.6% in Hungary to 78% in Austria. The resulting electricity capacity required to meet the set targets, depending on overall electricity consumption of the country, ranges between 0.4 TWh yr^{-1} in Estonia and 119 TWh yr^{-1} in France. National production capacity for *Miscanthus* for the four different land resource scenarios and resulting shares in national RES targets are shown in Table 3. For scenario 1, the lowest production capacity with 0.08 TWh yr^{-1} is found in Luxembourg and the highest with 61.2 TWh yr^{-1} in France. Possible contribution to national 2010 RES targets ranged from 3% in Finland to 1297% in Lithuania. Beside Lithuania the states of Hungary (872%), Estonia (706%) Poland (374%), Czech Republic (213%), and Latvia (163%) all show a production capacity that exceeds their set RES targets considerably. Increased production figures for scenario 2 reflect the differences in available land resources. The countries with highest productive capacities are France (83 TWh yr^{-1}), Poland (52 TWh yr^{-1}) and Germany (49 TWh yr^{-1}). The Irish Republic, due to its considerable increase in additional land resources in scenario 2, shows a 27 times higher

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Table 4 European regions (NUTS2) with highest electricity production capacity and their contribution to national RES targets set for 2010

	Country	Name of region	NUTS2 code	Modelled *Miscanthus* harvestable yield ($t\,ha^{-1}\,yr^{-1}$)	Area of available land ($ha \times 10^3$)	Achievable biomass ($t \times 10^6\,yr^{-1}$)	Electricity generation ($TWh\,yr^{-1}$)	Contribution (%) to national RES target
Scenario 1	Lithuania	Lietuva	LT00	16.0	473	7.6	11.0	1297
	Latvia	Latvija	LV00	13.8	373	5.1	7.5	163
	France	Centre	FR24	17.2	255	4.4	6.4	5
	Poland	Mazowieckie	PL12	19.0	230	4.4	6.4	48
	France	Midi-Pyrénées	FR62	15.2	284	4.3	6.3	5
	Poland	Wielkopolskie	PL41	16.9	235	4.0	5.8	44
	France	Pays de la Loire	FR51	16.6	231	3.8	5.6	5
	Poland	Lodzkie	PL11	19.2	168	3.2	4.7	35
	Denmark	Danmark	DK00	10.6	293	3.1	4.5	39
	France	Poitou-Charentes	FR53	15.1	202	3.1	4.5	4
	Poland	Lubelskie	PL31	19.1	155	3.0	4.3	33
	France	Rhône-Alpes	FR71	19.8	145	2.9	4.2	4
Scenario 2	Lithuania	Lietuva	LT00	16.7	487	8.1	11.9	1398
	Latvia	Latvija	LV00	14.4	380	5.5	8.0	173
	France	Centre	FR24	18.3	290	5.3	7.8	6
	France	Midi-Pyrénées	FR62	16.0	323	5.2	7.5	6
	France	Pays de la Loire	FR51	17.6	291	5.1	7.4	6
	Poland	Mazowieckie	PL12	19.9	236	4.7	6.8	51
	France	Rhône-Alpes	FR71	20.3	215	4.4	6.4	5
	France	Bourgogne	FR26	21.1	205	4.3	6.3	5
	Poland	Wielkopolskie	PL41	17.6	242	4.3	6.2	47
	France	Poitou-Charentes	FR53	16.0	229	3.7	5.3	4
	France	Auvergne	FR72	20.8	166	3.5	5.0	4
	France	Bretagne	FR52	14.8	229	3.4	5.0	4

Scenario 1, 10% arable land (equals current set aside land); Scenario 2, 10% agricultural land (arable land plus grassland).
RES, renewable energy sources.

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production capacity, and would as a result also be able to exceed its national 2010 RES target. Based on the land resources available in scenarios 3 and 4 respectively, 12 and 16 out of the 25 EU member states would be capable of reaching or exceeding their RES target set for 2010.

Table 4 shows the production capacity of *Miscanthus* for selected NUTS2 regions and the possible contribution to national RES targets for land resource scenarios 1 and 2. With the EU divided into 254 NUTS2 regions (245 are considered in this study) only the 12 best performing regions for the two scenarios are shown.

Since eight EU member states (Cyprus, Denmark, Estonia, Malta, Latvia, Lithuania, Luxembourg, and Slovenia) are represented by a single NUTS2 region their production figures are equal to their national production capacity. For scenarios 1 and 2, the largest land resources are available in the 'state' regions of Lithuania (LT00) 473 and 487×10^3 ha, Latvia (LV00) 373 and 380×10^3 ha, and Denmark (DK00) 293 and 323×10^3 ha. The highest achievable harvestable yields of 21.5 and 22.2 $t\,ha^{-1}\,yr^{-1}$, respectively, for the two scenarios was found in the Italian region of Lombardia (ITC4). ITC4 though, due to its small land resources, is not one of the best performing regions. The region with the highest biomass potential for both scenarios (7.6 and $8.1 \times 10^6\,t\,yr^{-1}$) is Lithuania (LT00). Estimated regional electricity offsets for the top 12 regions considered ranges from $4.2\,TWh\,yr^{-1}$ in the region Rhône-Alpes (FR71) to $11.0\,TWh\,yr^{-1}$ in Lithuania (LT00) for scenario 1 and from $5.0\,TWh\,yr^{-1}$ in the region Bretagne (FR52) to 11.9 $TWh\,yr^{-1}$ in Lithuania for scenario 2. The contribution of calculated electricity capacities to the national RES targets for all NUTS2 regions for the two scenarios (Fig. 3a and b) varies considerably from $<1\%$ in 100 of the regions for scenario 1 and 70 of the regions for scenario 2 to a respective capacity of 13 and 14 times the required quantity in Lithuania (LT00).

Discussion

Data quality

The objective of this work was to use GIS spatial analysis to predict *Miscanthus* biomass production on national and regional levels across Europe. The quality of the analysis is ultimately dependent on the spatial resolution of the data inputs into the conceptual model illustrated in Fig. 1. The data inputs with the lowest resolution were the climate information and the estimates of PAW which are available as gridded point layers with a resolution of $0.5 \times 0.5°$. This resolution does not allow the discrimination of small areas of dissimilar values or the detection of small gradual changes. Although this resolution was sufficient for the spatial scales adopted in this paper, the model outputs do not reflect the true heterogeneity of the mapped parameters at a small scale and could therefore lead to predictive errors at particular site locations that are divergent from the gridded mean values. Nevertheless, the outputs from this analysis are a significant improvement on those of Clifton-Brown *et al.* (2004) because of a combination, of more detailed and advanced spatial analyses, higher geographical resolution, and extended geographic coverage.

Land use scenarios

The four land use scenarios adopted here all show that there is significant potential for *Miscanthus* to make a contribution to biomass energy production in many European countries. The first scenario, examining the potential of current set aside, could theoretically be implemented immediately with considerable environmental benefits (Smith *et al.*, 2000). The second scenario, taking 10% of both arable and pasture land may need more careful consideration for two reasons. Firstly, some authors suggest that ground preparation for planting (ploughing and tilling) will lead to significant CO_2 emissions in the short term (Davidson & Ackerman, 1993) reducing the C mitigation benefit of biomass. However, measurements made in Ireland of the CO_2 released when old pasture was ploughed and reseeded showed that losses at ploughing were recovered by the new crop within a year (Clifton-Brown *et al.*, 2005). Secondly, satellite imagery used in developing the PELCOM land use categories does not provide detail on the type of pasture converted to *Miscanthus* cultivation. For example, from this database there is no distinction between improved or seminatural pasture land. To maximise the benefit from biomass crops, it would be useful to omit the potentially less productive and environmentally sensitive seminatural grasslands from biomass land use analysis.

In the third and fourth scenarios, we examine the theoretical potential of increasing land use for biomass production to very high levels. These scenarios are considered plausible by Thrän *et al.* (2006) who base their projections on high energy prices while considering principle constraints of food production, impacts on hydrology, and landscape aesthetics.

The MISCANMOD model platform

To consider the impact of the use of different land areas allocated to growing *Miscanthus* on RES, MISCANMOD was run on the mean climate data to provide yield estimates. To verify the model predictions, outputs from MISCANMOD have been shown to closely predict peak

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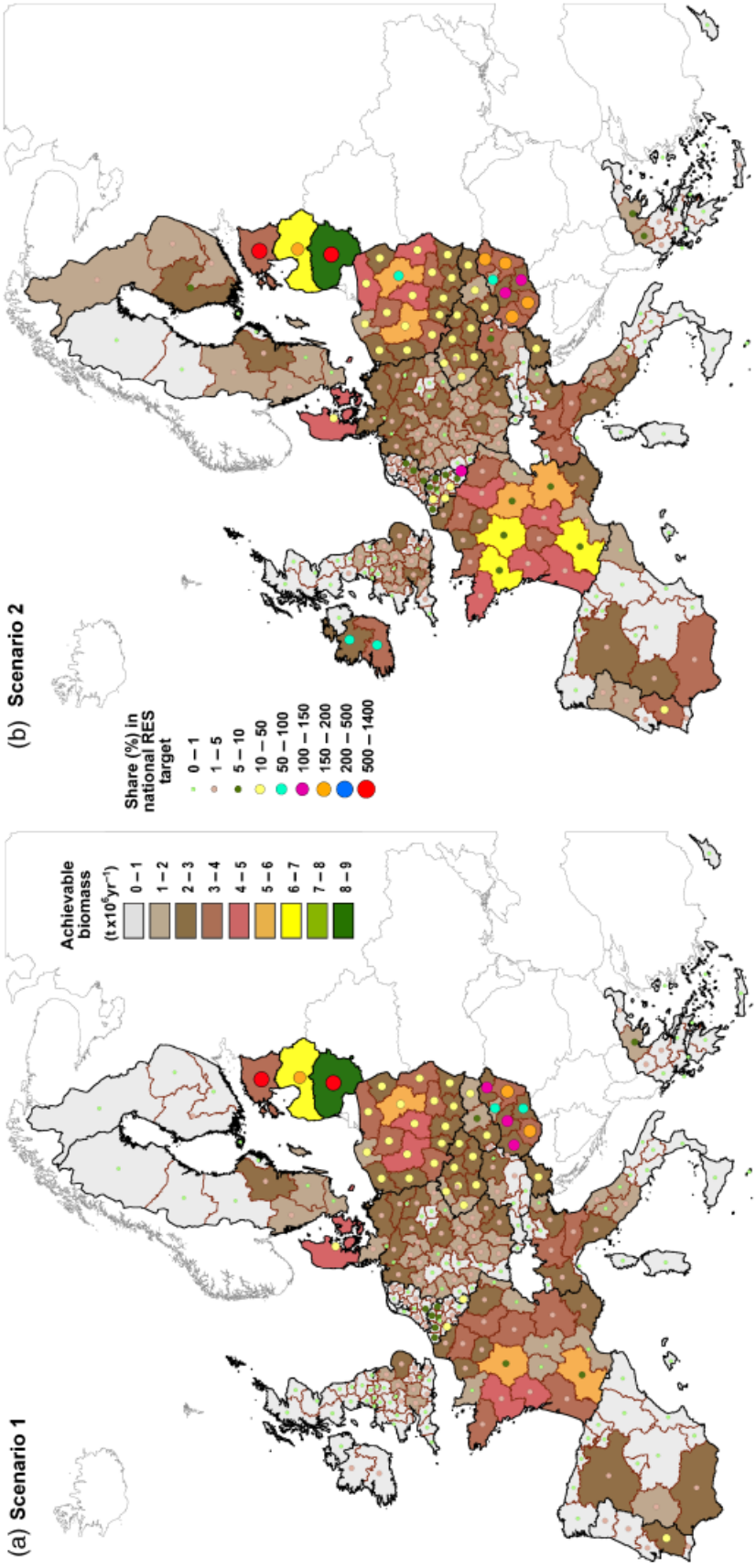

Fig. 3 (a) *Miscanthus* biomass potential for land resource scenario 1 (10% arable land) and (b) scenario 2 (10% agricultural land). Achievable biomass is the product of suitable land area and peak autumn yield above 10 t DM ha^{-1} yr^{-1} minus 33% reduction for losses due to delayed harvest. Circles indicate the share that each region can contribute to the national renewable energy sources target set for 2010.

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autumn yields determined at a number of field trial sites in the EU (Clifton-Brown *et al.*, 2004). However, MISCANMOD has the potential for further development, particularly in predicting yields under stress conditions such as water stress and also in assessing the relative performance of different *Miscanthus* genotypes. Currently MISCANMOD is parameterized for one genotype only but in the future as new, possibly more productive, genotypes are released by plant breeders it will be necessary to modify it to account for the varying performance of different genotypes under the range of European climatic conditions.

Regional biomass potential

National or regional biomass potential of *Miscanthus* for the adopted spatial units (EU, individual EU member states, and NUTS2 regions) is the product of available land resources and achievable yield. The presence of the top regions in Table 4 is accounted for mainly by their large land resources rather than high dry matter yield per hectare.

National RES targets for 2010, proposed individually by each member state, range considerably between 3.6% in Hungary and 78% in Austria. Under land resource scenario 2 the combined regional production capacity of seven member states equals or exceeds the national RES target. These countries therefore represent potential biomass exporters. However, as can be seen in Table 3, higher rankings based on contribution to RES are mainly due to low or moderate national RES targets. Possible future export potentials will, therefore, depend largely on the development of the domestic biomass demand. Adopting NUTS2 regions as spatial units allows downscaling to regional level. However, NUTS2 regions, despite being adopted by Eurostat as a coherent structure of territorial distribution, can vary considerably in size (Fig. 3). For example, some states such as Denmark (DK00), or Lithuania (LT00) are represented by a single NUTS2 ('state') region while other states which are comparable or smaller in size are divided into two or more regions. In contrast, Germany is divided into 41 comparatively small regions. The resulting moderate regional *Miscanthus* biomass capacities for Germany do not, therefore, reflect the fact that it has the third largest national production potential. Consequently, the ranking of individual NUTS2 regions shown in Table 4 needs careful interpretation by policy makers.

Estimated electricity offset

The modelled harvestable yields of *Miscanthus* integrated with the land cover classification as defined by PELCOM grid were used to assess national and regional biomass potential and calculate possible energy offset for the four different land resource scenarios. The adopted national electricity projections from 2000 to 2030 are based on a growing share of RES in EU primary energy demand, as well as an increased contribution of RES to electricity production (European-Commission, 2004b). Because only incomplete energy statistics are available for NUTS2 regions the calculated regional electricity potentials were related to national RES targets. With no new indicative RES targets yet set by the EU for the period after 2010 the production capacity of *Miscanthus* for the presented land resource scenarios were related to the RES targets set for 2010.

In conclusion, the GIS data processing and spatial analysis together with a simple growth model (MISCANMOD) has been used to predict harvestable yield of *Miscanthus* and to calculate electricity offset within the EU-25 under four different land resource scenarios. The GIS based methods developed here describe a sound modelling framework that is only limited by the coarse resolution of some of the source data currently available. Being consistent with the territorial units adopted by the EU, the created spatial database can be extended with additional socioeconomic information produced by Eurostat for bio-energy planning on regional and national levels. In the future the GIS database can be easily updated and extended when new datasets become available and offers greater flexibility in adjusting the model to changing policies, diverse climate and energy scenarios or improved spatial resolution of data. We believe that the approach presented here demonstrates how practical information needed for policy makers can be produced by integrating geospatial analyses and modelling techniques with knowledge derived from field sites.

Acknowledgements

We thank Dr David Viner for providing access to the CRU European climate data grid, Dr Mark New and Prof. Nigel Arnell for supplying derived radiation grid and estimates of Penman-Monteith evaporation respectively. The authors are grateful to all those who participated in the European *Miscanthus* Improvement project. This work was part funded by the EU contracts FAIR3-CT96–1392 (EMI), FAIR3-CT96-1707 (EMN) and SSPE-CT-2005-006581 (ENFA).

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