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Modelling the spatial allocation of second-generation feedstock (lignocellulosic crops) in Europe

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This paper presents a modelling approach for the spatial allocation of second-generation feedstock (lignocellulosic crops) under a reference policy scenario in European Union of 28 Member State (EU-28). The land-use modelling platform (LUMP) was used in order to simulate the land-use changes from 2010 to 2050. Within the LUMP, the land demand for these lignocellulosic energy crops was derived from the Common Agricultural Policy Regionalised Impact analysis model. Suitability maps were generated for two main energy crop groups: herbaceous and woody lignocellulosic crops, using multicriteria analysis techniques. Biophysical factors (climate, soil properties and topographical aspects), natural and artificial constraints and location-specific land categories were defined as relevant components within the platform. A sensitivity analysis determined the most influential factors to be temperature, precipitation, length of growing period and number of frost-free days. The results of the modelling exercise in the LUMP reflect the significant renewable energy contribution from energy crops in EU-28, which was estimated to be between 2.3 EJ/year (in 2020) and 6.3 EJ/year (in 2050), accounting for 2.3% and 9.6% of total energy consumption in the EU-28. The results of the allocation were aggregated at regional level to analyse trends. Regions with considerably high demand were identified in Germany, the United Kingdom and Poland.

Keywords: land-use modelling; renewable energy; crop suitability map; energy crops; multicriteria analysis

1. Introduction

The Climate and Energy legislative package adopted in December 2008 established a range of measures to mitigate climate change and promote renewable energy (Council of the European Union 2008). This package was designed to aid in achieving the EU's overall environmental targets by 2020: a 20% reduction in greenhouse gas (GHG) emissions from 1990 levels, a 20% share of renewable energy in the EU's total energy consumption and a 20% improvement in the EU's energy efficiency. The Renewable Energy Directive (RED) plays an important role within this package aiming to promote the use of renewable sources for the energy and transport sectors (2009/28/EC) (EC 2009a).

With this push towards using more sustainable resources, energy crops are foreseen to play an increasingly important role. As opposed to first-generation energy crops (most frequently derived from food crops), here we look at the trends associated with non-food

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crops, the so-called second-generation biofuels. These include mainly agricultural residues and lignocellulosic crops grown specifically for their fuel value (BEE Project 2010). The main advantages of using second-generation energy crops are that most of the crops are able to adapt to a wide range of climate and soils conditions, meaning that they can successfully be grown on lands not ecologically suited for conventional farming practices (Land Use Consultants 2007, UNICT 2009b, Fernando *et al*. 2010). Degraded and contaminated lands could therefore potentially be recovered by planting such energy crops, so reducing the current land abandonment in the agricultural sector (Goor *et al*. 2001, 2003, Van Slycken *et al*. 2013). Energy crops can additionally reduce soil erosion and enhance physical soil properties (soil water absorption capacity and nutrients) (Fernandez and Curt 2005, Isebrands 2007, De Mastro *et al*. 2011).

It has been estimated that, in Europe, some 20.3 million hectares of land could potentially be devoted to the cultivation of non-food crops by 2020, mainly through the exploitation of fallow land (UNICT 2009a). It should be noted, however, that intensive agriculture practices for the bioenergy production may have some negative impacts on soil function and quality, on water quantity and quality, high biodiversity value areas, air quality and food security, among others. These negative impacts can be minimized by selecting crops that are well-suited to the local biophysical conditions and using good management practices (for instance, use of pesticide and fertilizer; BEE Project 2010).

Several studies have recently focused on the evaluation of the biomass potential from energy crops at various scales, including regional, national and European. Fiorese and Guariso (2010) detailed a Geographical Information System (GIS)-based methodology to maximize energy production from herbaceous and arboreous crops at a regional scale, considering as available marginal land and set-aside land. A methodology for biofuel productivity assessment is presented in Fischer *et al*. (2010a, 2010b). The global agro-ecological zones methodology takes into account, among others, climate characteristics, plant requirements, soil and terrain properties, and current land use/cover, to calculate potential biomass production and energy yield. This has been applied in Eastern Europe, Northern and Central Asia to assess the biomass potential of miscanthus, willow and poplar (Fischer *et al*. 2005), as well as in Spain for cardoon (Garcia *et al*. 2008, De Mastro *et al*. 2011). In the United Kingdom, Bauen *et al*. (2010) and Aylott *et al*. (2008) estimated the potential of lignocellulosic energy crops based on productivity models which also included climatic, soil and land-use factors.

In terms of lignocellulosic feedstock, second-generation biofuel generally falls into two categories: herbaceous and woody (DEFRA 2004, UNCTAD 2008, Baraniecki *et al*. 2009, Fischer *et al*. 2010a). When mentioning lignocellulosic energy crops in the context of this study, we specifically refer to five herbaceous species (miscanthus, switchgrass, reed canary, giant reed and cardoon) and three woody species (willow, poplar and eucalyptus). We thus exclude residues from agricultural crops and forest species. In this study, we look at the suitability of land for the growth, and therefore the allocation, of these crops over the European Union of 28 Member State (EU-28) countries on an annual basis for the period 2010–2050. We used a spatial land-use modelling platform (LUMP) to determine future allocation of these individual crops, based on biophysical suitability maps. A policy reference scenario was used, which takes into account current EU policy. The novelty of this work lies in the application of this dynamic land-use model to determine the most suitable allocation of these eight energy crops for the whole EU-28 territory.

The remainder of this article is organized as follows. In Section 2, we briefly describe the configuration of the LUMP adopted in this context, the calculation of the suitability layers and other main methodological aspects. The results of the modelling exercise are presented and discussed at regional level in Section 3, and the main conclusions are addressed in Section 4.

2. Materials and methods

2.1. An overview of the LUMP

The LUMP (EC 2013a) was developed for the Institute for Environment and Sustainability of the Joint Research Centre to support the policy needs of the European Commission, providing a vision of possible futures by comparing simulated scenarios and policy options at European level. The LUMP is a computational dynamic spatial modelling platform which simulates future annual land-use changes based on biophysical and socio-economic drivers from year 2010 up to 2050. As shown in Figure 1, the LUMP is composed of three main modules: the land demand module, the land allocation module and the impact assessment indicator module. The first module determines the amount of land claimed per sector, driven by different sectoral socio-economic models. The Common Agricultural Policy Regionalised Impact (CAPRI) model (Britz 2011) is used to determined agricultural demands, GLOBIOM/G4M (IIASA 2012) for the forestry sector and GEM-3M (GEM-3M 2012) for the industrial sector. The evolution of residential areas (urban land) is driven by demographic projections (EUROSTAT 2010).

The core of the modelling platform, the land allocation module, is based on the dynamic simulation of competitions between land-use classes, operating at 100 m (cell size) spatial resolution. The allocation of land uses to space is governed by a land-use optimization approach, in which discrete land-use transitions occur per grid cell per time-step (yearly). The suitability of locations for various land-use types is determined by

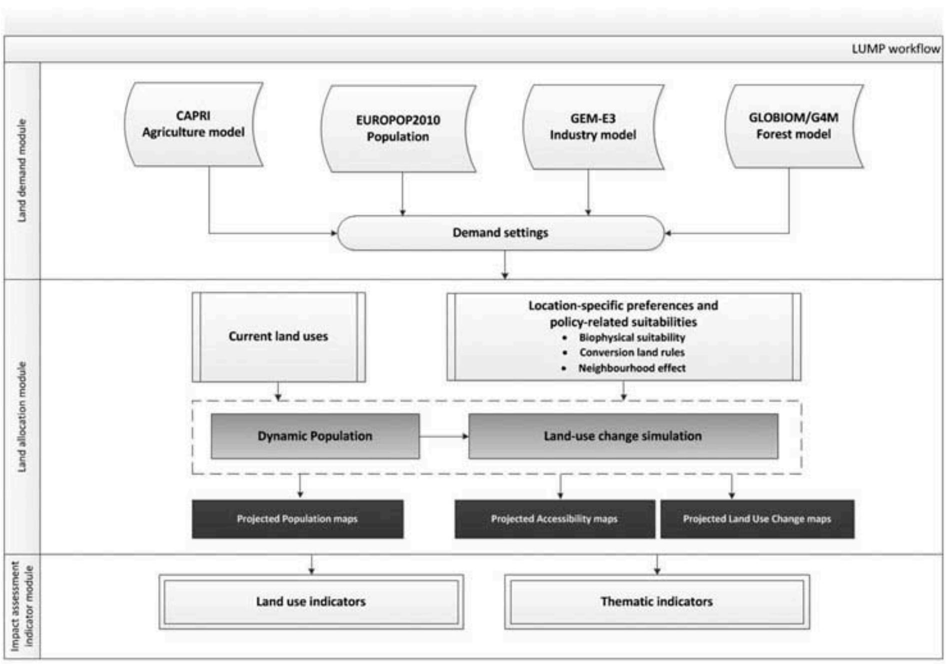

Figure 1. Modular structure of the LUMP and the main models and data set included.

geophysical factors (slope, orientation and elevation), socio-economic factors (potential accessibility, accessibility to towns and distance to roads) and neighbourhood interactions between land uses. Besides these components, an 'allow matrix' informs the model on which transitions are permitted,[1] and a 'transition cost matrix' informs the model on the likelihood of pairwise transitions (for instance, from pasture to forest). The main, final output of the allocation module is a land-use map with 17[2] modelled land-use classes. Potential accessibility and population distribution maps are also endogenously computed by the model as a result of the simulation.

The third module refers to the impact analysis indicators module which is used on project-specific basis to analyse the resulting land-use patterns and trends. More detailed information on the allocation algorithms, previous configurations of the LUMP, implementation and the land-use transitions can be found in Lavalle *et al*. (2011a, 2011b, 2011c), Verburg *et al*. (2008), Hellmann and Verburg (2010), Britz *et al*. (2011), Mubareka *et al*. (2013) and Object vision (2013).

2.2. Defining the reference scenario

In order to reflect the mandatory GHG emission and energy targets set for 2020, a policy reference scenario was defined in the LUMP as a benchmark for policy scenarios with long-term targets. The definition of the reference scenario was given in the Energy Trends to 2030 (EC 2009b) document and in the Energy Roadmap 2050 (EC 2011). The scenario also includes the national targets under the Renewables directive and the Emissions Trading Scheme Directive.

From a modelling point of view within the LUMP, the reference scenario is based on the EUCLIMIT[3] modelling framework (EUCLIMIT 2012), which supports the European Commission in undertaking impact assessments and analysing policy options for implementing the Climate and Energy package, among other directives. Other policies considered because of their territorial impact include the RED, the Common Agricultural Policy (CAP), the TEN-T Transport Network and the 2020 Biodiversity Strategy. The implementation of the reference scenario in the LUMP allowed to assess the impact of the EU policies on future land use. A detailed description of the reference scenario is given in Lavalle *et al*. (2013).

Owing to the relevance in this study, several aspects of the RED promoting the use of second-generation energy crops and ensuring the use of sustainable biofuels and bioliquids were taken into account specifically in defining the biophysical suitability maps. These include the restriction of biomass production in protected areas (national and international), restriction on areas with high biodiversity value and land with high carbon stock (primary forest and wooded land, wetlands and peatlands), as well as promoting the use of surplus land.[4] The Directive also sets a maximum slope limit for cultivation and requires that only perennial crops can be grown on sites susceptible to soil erosion; that management practices (crop choice and yields) be adapted to local biophysical conditions, and water consumption to regional resources (BEE Project 2010).

2.3. Modelling second-generation feedstock in the LUMP

The LUMP is continuously undergoing development in order to answer specific questions related to different sectors to assessing EU policy alternatives. However, the methods section of this paper only describes the specific aspects of the configuration relevant for modelling the spatial allocation of second-generation feedstock (lignocellulosic energy crops) in the LUMP.

2.3.1. *The land demand module*

According to Figure 1, the land demand module is where demand, also referred as land claims, for different land uses is defined. Land demand for second-generation feedstock for the period 2010–2050 was derived from the CAPRI model. CAPRI is a spatial agro-economic model of agricultural commodity markets at European scale (Britz 2011) which assess the impacts of the CAP at NUTS 0 and NUTS 2 level[5] and it is a component of the EUCLIMIT model framework. The recent incorporation of land demand for energy crops (New Energy Crops (NECR), 'ligneous') in the CAPRI model was the main reason for developing a methodology to also model the spatial allocation of these crops in the LUMP. In order to do this, eight representative energy crops were considered, which together make up a new land-use class called NECR.

2.3.2. *The land allocation module*

These land demands are passed onto the land allocation module. The allocation is based on the dynamic competition between land uses incorporating biophysical suitability, neighbourhood effects, transitions rules and policy-related effects (Lavalle *et al*. 2011a, 2013, Mubareka *et al*. 2013). An important part of this mechanism is the calculation of biophysical suitability maps specific to each crop type (see Section 2.3.2.1). The specificities of the policy-related land categories (restrictions on areas and promotion in others) are also further detailed in Section 2.3.2.2.

2.3.2.1. Generating biophysical suitability maps for second-*generation (lignocellulosic) feedstock.* Suitability maps were created for each of the eight most representative species of second-generation feedstock in Europe using multicriteria analysis (MCA). The selected species were chosen due to their widespread geographical coverage and the abundant availability of literature as compared with other species used for energy purposes. The herbaceous lignocellulosic crops considered were miscanthus (*Miscanthus* spp.), switchgrass (*Panicum virgatum*), reed canary (*Phalaris arundinacea*), giant reed (*Arundo donax*) and cardoon (*Cynara cardunculus*). Woody lignocellulosic tree crops considered were willow (*Salix* spp.), poplar (*Populus* spp.) and eucalyptus (*Eucalyptus* spp.).

Biophysical and environmental information for each of these crops is required in order to identify the most suitable location for their successful development, according to their adaptability to different regions of Europe. In terms of ecological requirements, a number of relevant factors were established according to topographical aspects, soil quality (physical and chemical characteristics) and climate conditions. Eleven factor maps (biophysical variables) were identified as being the most relevant according to an extensive literature review (Esser 1993, DEFRA 2004, Fernandez and Curt 2005, Isebrands 2007, Land Use Consultants 2007, Aylott *et al*. 2008, Garcia *et al*. 2008, Baraniecki *et al*. 2009, BIOCARD 2009, Finch *et al*. 2009, The Research Park 2009, UNICT, 2009a, 2009b, Wisconsin Reed Canary Grass 2009, Bauen *et al*. 2010, Fernando *et al*. 2010, Fiorese and Guariso 2010, Fischer *et al*. 2010a, 2010b, Teagasc 2010, De Mastro *et al*. 2011, Milovanović *et al*. 2011, Teagasc and AFBI 2011, IEA bioenergy 2012, Kuhlman *et al*. 2013) and consultation with experts. These selected factors were temperature, precipitation, length growing period (LGP), frost-free days (FFDs), soil pH, soil texture, soil drained, soil type, slope and salinity. Each factor corresponds to a spatial thematic layer with Pan-European extent. Biophysical suitability maps were done in a GIS environment using ETRS89 reference system and Lambert Azimuthal equal area projection. A description of each factor considered is given in Table 1.

These biophysical variables (factor maps) were combined to create a suitability map for each energy crop in the context of MCA technique. Six suitability classes were defined to assigned numerical values to each class belonging to each factor map. The classes were classified as follows: very suitable (highest adaptability), suitable, moderately suitable, low suitability, poorly suitable (low adaptability) and not suitable. A quantitative scoring[6] was applied on the basis of individual evaluation for the set of classes of each factor map (see Table A1), through value judgement and literature review. Each factor map was normalized from 0 (poorly suitable) to 100 (very suitable) in order to convert them to the same measure.

The weighted linear addition (WLA) technique was applied in order to integrate all individual factors maps and to determine the overall suitability (appropriateness of the land to grow the specific energy crops) at each location (pixel) in a GIS environment.[7] By integrating all biophysical factors map in one, it is possible to quantify the final suitability of each location (pixel) by multiplying the value by its given weight, as shown in Equation (1):

$$r_i = \sum_{j=1}^{n} w_j v_j \qquad (1)$$

where r_i is the suitability level of each location (pixel) i, w_j is the weight of each factor j and v_j is the assigned value of pixel i in factor j. The annual temperature and the annual precipitation were assigned twice the weight of the other factors in order to reflect the relative importance of these two factors within the context of the study.

The last step of an MCA is to carry out a sensitivity analysis of the factors involved in the previous stage. This was done using the SimLav V2.2.1 program (SIMLAB 2013) developed by the Joint Research Centre of the European Commission, which uses the Monte Carlo method to determine the uncertainty level of the model predictions and input variables, with the aim of identifying the effect of factor and weight variations on the model results. This ensures the results are more reliable and identifies the factors by which they are significantly influenced (Saltelli *et al*. 2000, Gómez and Barredo 2005). This analysis was performed using the global Sobol method, which was considered to be the most complete since it studies the whole range of factors and was also the most suitable for GIS environments. For a more detailed description of the procedure used in SimLav, see also Perpiña *et al*. (2013).

2.3.2.2. Specific policy considerations. As can be seen in Figure 1, EU-specific policies, conversion rules, neighbourhood effects and current land use are key factors to allocate land in the LUMP. EU-specific policies applied to renewable energy (particularly for energy crops) are considered in Tables 2 and 3 as constraints (natural and artificial) and location-specific land categories, respectively. According to the RED, specifically Article 17: sustainability criteria for biofuels and bioliquids indicate that biofuels and bioliquids shall not be made from raw material obtained from land with specific characteristics. In order to address this legal requirement, nationally designed areas and Natural 2000 sites

Table 1. Biophysical variables considered in the spatial allocation of second-generation (lignocellulosic) feedstock.

Biophysical variables	Description and sources
Temperature	The mean annual temperature in °C was divided into seven classes with 5° intervals from −10°C to >20°C. Temperature was provided by the European Food Safety Authority (EFSA), Spatial Data Version 1.1 (EC 2013b), processed in 2012, 1 km resolution.
Precipitation	The mean annual precipitation (in mm) was divided into seven classes with 200 mm intervals, from 0 to >1000 mm. Precipitation was provided by EFSA (EC 2013b), processed in 2012, 1 km resolution.
Soil pH	Spatial layer of topsoil pH for the dominant soil was divided into five classes from <4 to >9. Soil pH exceeding these extremes is considered not favourable for crop growth. Soil pH was provided by EFSA (EC 2013b), which is based on HWSD (FAO/IIASA/ISRIC/ISSCAS/JRC 2012), 1 km resolution.
Soil texture	Five classes were defined: coarse, medium, medium fine, fine and very fine. Soil texture with less than 18% clay, more than 65% sand, or with stones, boulders or rock at the surface are considered not favourable for crop growth. The texture classes were compiled from the Soil Information System for the MARS Crop Yield Forecasting System (SINFO project) (EC 2013c) which is based on the European Soil Database (ESDB).
Soil depth	Soil depth is important to ensure maximum root development. Soils with depth limitations within 50 cm of the surface caused by the presence of coherent hard rock or shallow soils were considered not favourable for crop growth. This spatial layer is divided into eight classes from <10 to >120 cm. The soil depth classes were compiled from the SINFO project (EC 2013c) which is based on the ESDB (EC 2013d).
Soil type	This spatial layer is divided into eight classes. Clayey, sandy and loamy materials are suitable for these crops. High clay contents mean poor draination, oxygenation and root development, while high sand contents leads to excessively drained soils with low nutrients levels (Schuette 2000). Soil type is based on the ESDB (EC 2013d), 10 km resolution.
LGP	The number of days when the average daily temperature is above a certain temperature threshold. LGPt5 is selected, establishing 5°C as threshold, and using 16 classes from 0 to 365 days, most with an interval of 30 days. LGP data were provided by IIASA/FAO (2013).
FFDs	The number of days between the last spring frost and the first fall frost. This determines the length of time available for crop production, as well as the type of crops that can be grown in a particular region. FFD spatial data were classified into four classes from 0 to >300 days with 100-days intervals. FFD data were provided by IIASA/FAO (2013).
Soil drainage	The drainage classes are derived based on FAO soil name, agricultural limiting phases and topsoil texture. This spatial layer is divided into seven classes, from excessively drained to very poorly drained soils. Imperfect, poor and very poorly drained soils are considered not favourable for crop growth. The soil drainage classes were compiled from the SINFO project (EC 2013c) which is based on the ESDB.
Slope	Derived from the elevation was divided into six classes: 0–2%, 2–5%, 5–8%, 8–16%, 16–30% and >30%. Flat areas or with a slope <8% are the most appropriated for crop growth. Slopes in excess of 16% will provide difficulty for harvesting machinery. Elevation comes from Shuttle Radar Topographic Mission (NASA 2013), which is used to derive the slope at 100 m resolution.

Table 2. Natural and artificial constraints considered in allocating energy crops.

Constraints	Description
Nationally designated areas	Raster layer holds information about protected sites and national legislative instruments, which directly or indirectly create protected areas. The spatial layers were provided by the Environment European Agency (EEA) (EEA 2013).
Nature 2000 network	Raster layer of European network of protected sites designated by EU Member States under the Birds Directive and the Habitats Directive. The spatial layers were provided by the EEA (EEA 2013).
Current land use	Artificial surfaces, peatlands, wetlands and water bodies were excluded in allocating energy crops, from the 2006 Corine Land Cover map (Batista e Silva *et al*. 2013) in its refined version.

Table 3. Location-specific categories considered in planting energy crops, mainly related to marginal and contaminated lands.

Location-specific categories	Description
Saline concentration	Medium salinity concentration areas are proposed as potential locations for energy crops, where food crops are affected by moderate salinity. High-salinity concentration may kill the crop (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). The saline concentration areas were compiled from the SINFO project (EC 2013c), based on ESDB.
Severe erosion areas	Severe erosion areas are unfavourable for agriculture due to the lack of soil nutrients and drainage problems, reducing soil productivity. Very strong, strong and moderately strong erodibility levels are proposed as potential locations for planting energy crops (EC 2013e).
Contaminated lands	Contaminated land with high concentrations of Cd, Cu, Cr, Pb, Ni and Zn should not be used for agriculture production. Spatial layers for each heavy metal were used in order to establish a threshold from which the area is considered contaminated (Micó *et al*. 2007). Heavy metals concentration (mg/kg) spatial data was provided by the European soil Portal (Soil Threats Data), and elaborated from the FOREGS Geochemical database at 5 km resolution (Lado *et al*. 2008).

were excluded, as well as the built-up land-cover classes (i.e. urban, industry and infrastructures), peatlands, wetlands and water bodies.

In addition, not all land-use/-cover classes can be converted into energy crops. Land for these crops is mainly allocated within the utilizable agriculture area (UAA) by the model, which includes arable land, pastures and permanents crops. The model also allows the allocation of lignocellulosic energy crops within forest areas but with higher conversion costs than within the UAA. As food production needs good quality soils, the reclamation of degraded, marginal[8] and abandoned lands can offer additional positive implications for planting energy crops in those areas. Location-specific physical characteristics such as soil salinity, severe erosion areas and contaminated lands were selected as location-specific land categories due to the selected energy species having particular ecological properties in order to be grown in those affected/degraded soils. The description of these categories is listed in Table 3.

2.3.2.3. Calibration in the LUMP for the reference scenario configuration. The LUMP is calibrated using multinomial logistic regression for both biophysical suitability and neighbourhood effects on a per-land-use basis (Loonen *et al*. 2007). The land-use model is calibrated using the observed land-use patterns in the refined version of the 2006 Corine Land Cover map (Batista e Silva *et al*. 2013). The layers used in the calibration for biophysical suitability are accessibility, slope, orientation and elevation. The neighbourhood taken into consideration for the neighbourhood effects calibration is the Moore neighbourhood. The influence of each land-use pair interaction within this neighbourhood is quantified for each country separately.

2.3.3. The impact assessment indicators module

In this module, several indicators were computed to assess the overall results. The share of energy crops per NUTS3 region was calculated, as well as their contribution to the overall gains and losses in other land uses over the whole EU-28 territory. In particular, the procedure is based on identifying the available land surface (see Section 2.3.2.2) where energy crops might be planted and the spatial allocation results from the LUMP's simulation (aggregated per NUTS3 level). Thematic maps are presented, illustrating the spatial changes in distribution of the energy crops for the NUTS3 regions from 2020 to 2050.

3. Results

3.1. Biophysical suitability maps for second-*generation feedstock*

The resulting suitability maps are shown per crop in Figure 2. The overall suitability map was obtained by merging the eight individual crop suitability maps generated (Figure 2, last frame), assuming that if at least one of the crops was suitable for a pixel the pixel remains suitable. The resulting raster layers, at 100 m (cell size) spatial resolution,[9] represent the degree of suitability of the land for each energy crop across Europe.

There is high variability in the resulting suitability maps for each energy crop, which reflects both the differences in adaptability between crops and the differences in physical characteristics of the land over Europe. The total suitable area varies strongly among the considered energy species. The herbaceous crops miscanthus, switchgrass and especially reed canary widely largely spread in Europe. Reed canary grass is adaptable to a wide range of temperature (from below 0°C to the warmest) and precipitation regimes, and can be grown from the south (Portugal, Spain, Italy and Greece) to the north of Europe, including southern Finland and Sweden. Cardoon and giant reed are much less dispersed, and are adaptable mostly to Mediterranean regions and the northwestern of France. With regard to woody crops, willow shows the highest adaptability, with highest suitability in central Europe, but covering even the eastern countries. As opposed to willow and poplar, eucalyptus is only adaptable to a limited range of possible sites in the Mediterranean regions since it requires warm temperatures (annual means between 12°C and 23°C) in order to grow successfully.

In summary, the most suitable areas in Europe for second-generation feedstock are the northwestern of France, north of Spain and the surrounding area of the strait of Gibraltar, from the north to the south of Italy except the Apennine Mountains, the central part of Portugal and Greece, the southern area of Romania and north of Bulgaria, and finally the western side of the United Kingdom and central and southeastern side of Ireland. The remaining central European countries have moderately suitability, and the eastern European countries have the lowest suitability for these energy crops.

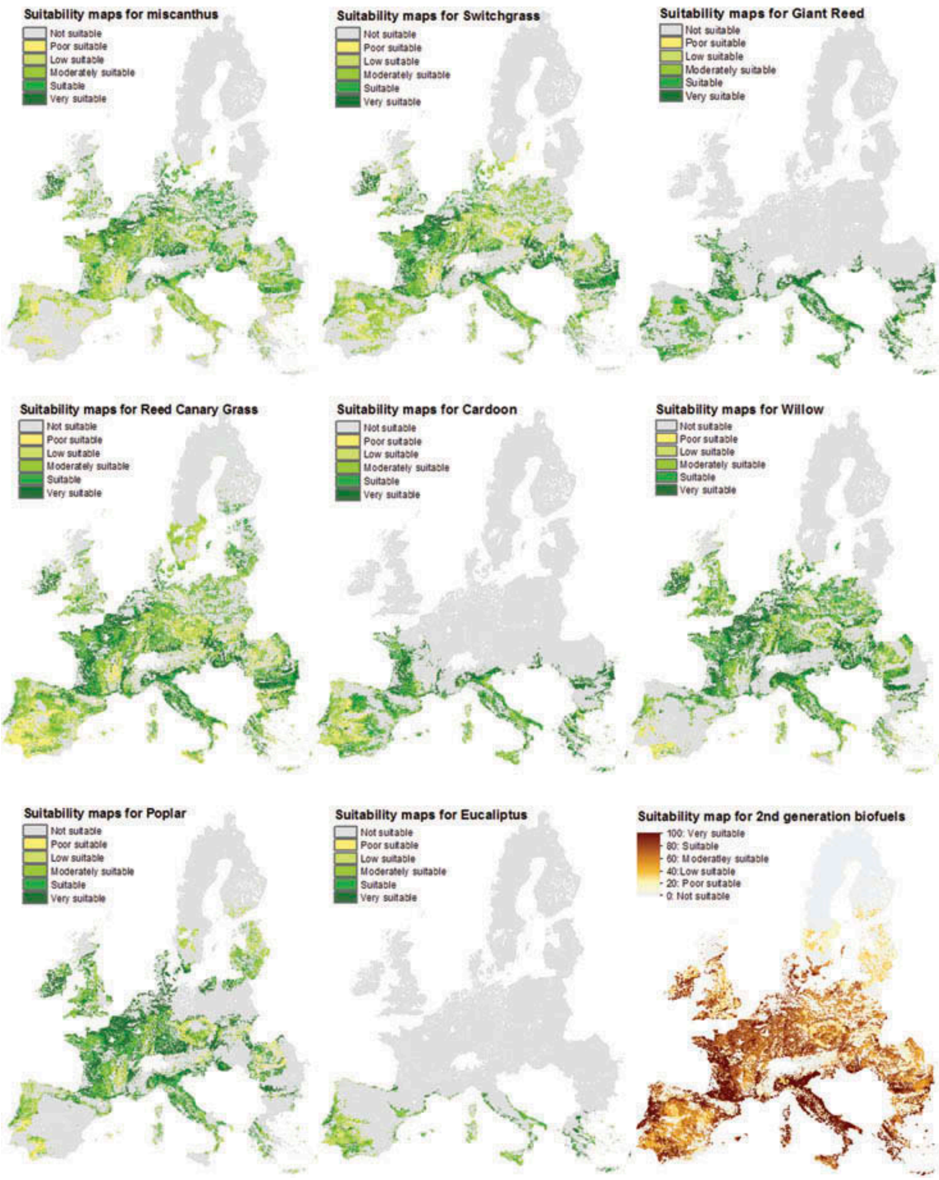

Figure 2. Suitability map for the individual energy crops (miscanthus, switchgrass, reed canary, giant reed, cardoon, willow, poplar and eucalyptus), with the last frame representing the overall suitability map for second-generation biofuels.

3.2. Spatial allocation of second-*generation feedstock in EU-28*

The resulting allocation of herbaceous and woody lignocellulosic energy crops for 20102050 was analysed at regional (NUTS3) and European level in a post-processing step.

Figure 3 shows the share of available land that was allocated energy crops per NUTS3 region. Second-generation energy crops are not present in Denmark, Greece, Croatia, Malta and Cyprus. In some other countries, energy crops disappear before

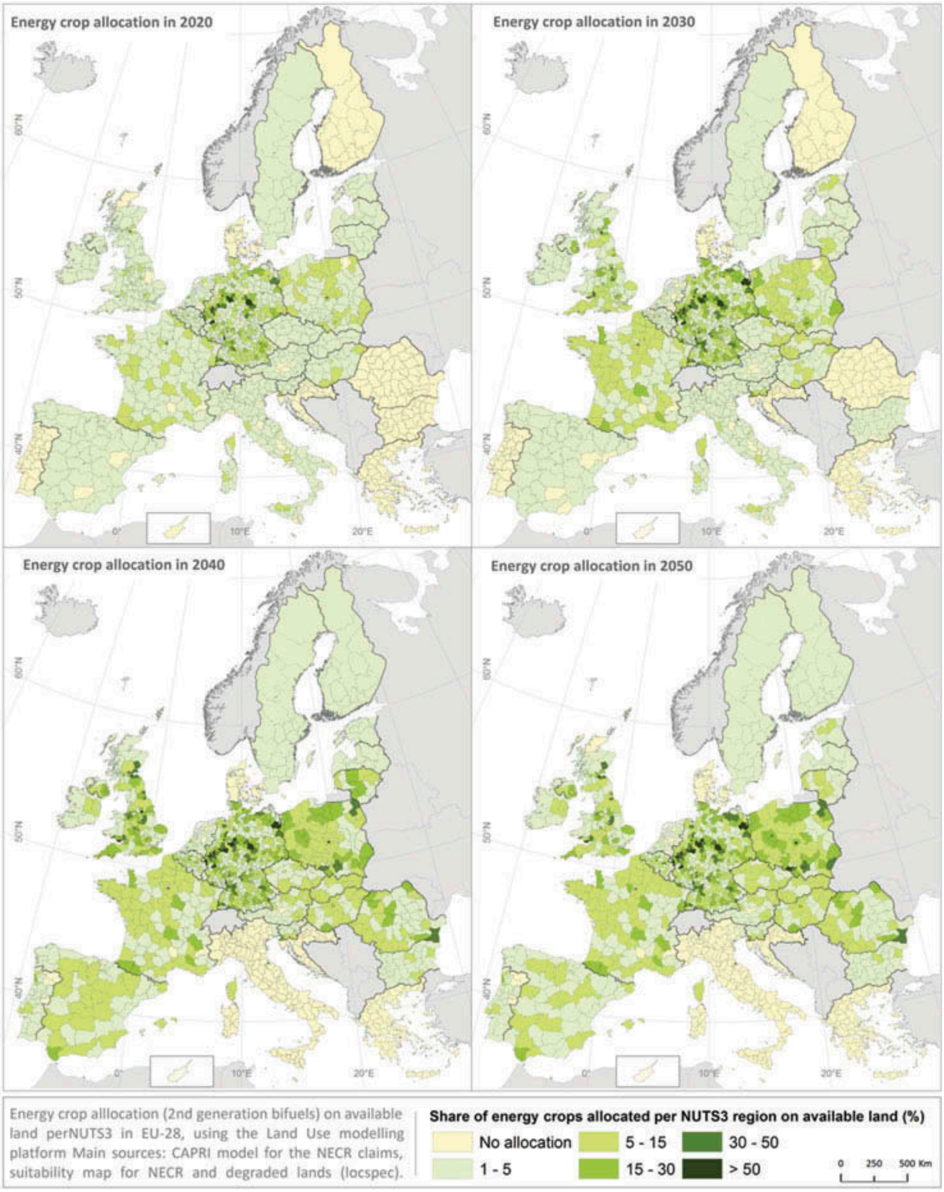

Figure 3. Share of energy crops allocated per NUTS3 region on available land (in %) in Europe between 2020 and 2050.

the end of the simulation period (2050). This is the case of Italy, where energy crops start to be allocated in 2020 and disappear from 2040 onward, following the projections of the CAPRI model. However, in the majority of the countries, energy crops appear later (either 2030 or 2040 depending on the country); examples are Portugal, Finland, Romania and Bulgaria. Germany, the United Kingdom and Poland which accumulate the highest share of land allocation for energy purposes per NUTS3 level.

Table 4. Land allocation, supply and energy potential in EU-28.

Simulation year	Land allocation (Gm^2)	Supply (1000 t)	Energy potential (EJ)
2020	5.28	1296.78	2.34
2030	8.17	2022.32	3.66
2040	14.8	3606.93	6.52
2050	14.5	3511.29	6.35

Table 4 shows aggregated figures at European level in terms of land allocated, supply and energy potential. The supply was corrected taking into account the proportion of land being allocated in the LUMP for the energy crops as compared to the CAPRI model supply. The energy potential was estimated using averaged conversion factors[10] for woody and herbaceous lignocellulosic crops, established at 18.1 GJ t^{-1} (De Wit and Faaij 2010). The energy potential ranges from 2.3 EJ y^{-1} up to 6.5 EJ y^{-1} in 2040 (decreasing by almost 3% in 2050) which might be used for bioenergy production. These figures represent a share of 3.5%, 5.5%, 9.8% and 9.6%[11] in 2020, 2030, 2040 and 2050, respectively, in final energy consumption in EU-28 which can be considered an important amount of energy source.

Gains and losses are defined as positive and negative transitions, respectively, between different land-use classes and each aggregated group is represented as percentage of total gains and losses, respectively. Figure 4 shows the total gains and losses over the whole EU-28 territory per aggregated land-use category over the period 2010–2050. The aggregated categories are agricultural land (or UAA; arable land, pastures and permanent crops); semi-natural vegetation; forest and artificial land (built-up areas). Of all the gains during that 40-year period in the EU-28, most are attributed to new energy crops (43%) and forest (34%). There is also a significant amount of conversion to new artificial land (10%) and UAA (12%). The land-use class that contributes most to the overall losses is the UAA (64.4%) and semi-natural vegetation (27.7%). This means that, overall,

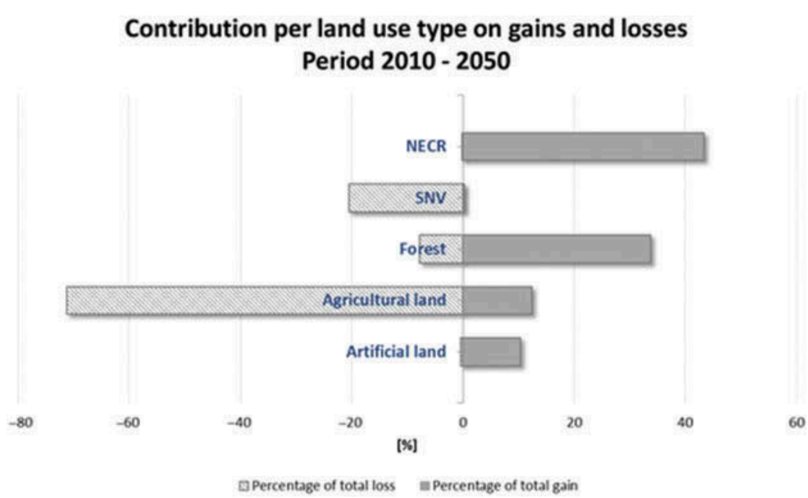

Figure 4. Overall contribution to gains and losses per land-use type categories between 2010 and 2050.

agricultural land is both converted to other uses and vice versa. Nevertheless, the total amount of agricultural land tends to decrease, especially due to the expansion of energy crops and forest.

Overall, according to the CAPRI model, the amount of land required for lignocellulosic energy crops increases progressively, starting in 2020, and the demand for land of other categories steadily decreases. The mechanism of the model is forced to allocate energy crops on less suitable areas for agricultural productivity. Comparing land projections between 2010 and 2050, the greatest land taken for lignocellulosic energy crops falls on arable land.

3.3. *Sensitivity analysis of the biophysical factors and weights*

The first step of the sensitivity analysis in SimLab was to introduce the type of distribution for each factor involved in the MCA and to generate the samples. Weights were also analysed in the study and a normal distribution was used with variations of ±25% and ±50% of the original value in order to observe the influence of each variable on the model. The applied model was based on the WLA method, as represented by Equation (1), assigning double weight to temperature and precipitation variables according to the literature review. Table 5 shows the resulting S_{Ti} (total sensitivity index) for each variable. The first column reflects the results with no variation in weighting. Four factors are seen to have a decisive effect on the variation of the model results, especially temperature (0.31), followed by precipitation (0.14), LGP (0.13) and FFD (0.102), which explain nearly 68% of the variation of the results in the model, even though the remaining factors contribute to a considerable extent as well.

The weight variations of ±25% and ±50% of their original values highlight the importance of several of the weights used in the analysis. The weights of temperature, LGP, precipitation and FFD are most important in the model. The weights of soil pH, soil depth, slope and texture, on the other hand, have very little influence on the results.

4. Conclusions

In general terms, modelling a new class in the LUMP implies to determine the elements which compose the three modules in the platform. Data for land demand, policy scenario

Table 5. Sensitivity analysis results per variable (factors and weights).

		Weights variation			
Variables (factors)	S_{Ti}	Variable	±25%	Variable	±50%
Temperature	0.311	Temperature	0.287	Temperature	0.270
Precipitation	0.142	LGP	0.118	LGP	0.086
LGP	0.127	Precipitation	0.106	Precipitation	0.074
FFD	0.102	FFD	0.099	Weight LGP	0.065
Drainage	0.076	Drainage	0.075	Drainage	0.059
Soil pH	0.066	Weight temperature	0.040	Slope	0.059
Soil type	0.058	Weight LGP	0.029	Soil depth	0.055
Slope	0.057	Weight precipitation	0.020	Weight precipitation	0.054
Soil depth	0.051	Weight FFD	0.019	Weight FFP	0.054
Soil texture	0.043	Weight slope	0.018	Weight slope	0.052

characteristics, biophysical suitabilities, spatial interaction between classes (neighbourhood effect), as well as conversion rules and transition costs between land uses, are the basic components to run a simulation in the LUMP. The recent incorporation of land demand for the NECR (ligno) in the CAPRI model was the main reason for modelling this new class, which leads to develop a new methodology to determine the spatial allocation of the most representative lignocellulosic energy crops in Europe.

One of the mechanisms to spatially allocate land uses in the LUMP is by means of suitability maps, in this particular case for second-generation feedstock (lignocellulosic energy crops). Eight suitability maps were generated for the selected crops: miscanthus, switchgrass, red canary grass, giant red, cardoon, willow, poplar and eucalyptus plantations. An MCA was undertaken to define the most important biophysical factors determining the suitability of land to grow these crops. These factors were temperature, precipitation, soil pH, soil type, soil drainage, soil depth, FFDs, long growing period, soil texture and slope. In addition to the suitability of land, it was taken into account that some land may also not be available for energy crop growth due to additional natural and artificial constraints (artificial surfaces, protected sites, areas with high biodiversity values, wetlands, peatlands and water bodies). In addition, location-specific land categories were established in order to encourage the recuperation of degraded, contaminated and marginal land.

The output of the spatial allocation of energy crops in the LUMP is represented as a simulation from 2010 to 2050. The main contribution of aggregated land-use types to the overall gains was attributed to lignocellulosic energy crops (43%) probably as a result of two drivers. First, the increasing amount of land demand for this commodity from the CAPRI model from 2020 onwards. Second, energy crops were encouraged to occupy areas with unfavourable biophysical characteristics (degraded and contaminated lands). On the other hand, the amount of UAA land required steadily decreases.

Finally, the sensitivity analysis, using the global variance-based Sobol method, provided information on the 10 factors and indicated those with the strongest influence on variations in the model results. From these results, it can be seen that the most important factors are temperature (0.31), precipitation (0.14), LGP (0.12) and FFD (0.102) which together accounted for 68% of variance. However, in view of the total figures, the total influence of each factor in the model is quite significant, with the total variance being fairly distributed. The conclusion that can be drawn from this, and which should be taken into account when undertaking similar studies, is that these four factors, being those with the greatest influence on the results, must be based on reliable spatial information. With regard to weight variations, we should also highlight the weights of LGP, temperature, precipitation and FFD which strongly influence the model.

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Notes

1. It can also be specified to define the number of years required for a transition to take place.

2. Urban, industrial, other arable, permanent crops, pastures, forest, transitional wood land shrub, cereals, maize, root crops, abandoned arable, abandoned permanents crops, abandoned pastures, abandoned urban, abandoned industry, energy crops and scrub herbaceous vegetation association. As a fix classes are considered: infrastructure, other nature, wetlands, water bodies and green urban areas.
3. Development and application of EU economy-wide climate change mitigation modelling capacity.
4. Surplus lands are those lands that are not needed any more for the production of food and feed crops or for other purposes. Degraded and low productivity lands can be included in this category.
5. Nomenclature of territorial units for statistics. http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction
6. The highest suitability was assigned a value of 5, the lowest was assigned 1 and not suitable areas were assigned 0.
7. A specific spatial tool was used to overlap several rasters, multiplying each by their given weight and summing them together.
8. In the marginal land category is included several types of soil in which some of the soil parameters are out of the optimal range (marginality of soil). These parameters may be salinity concentration, pH, erosion, soil with mechanical limitations, water deficit, extremely temperatures, steep slopes, etc..
9. Bilinear resampling was used to homogenize the data sources at a spatial resolution of 1 hectare (100 × 100 m).
10. Conversion factor from energy crops to biofuel energy equivalent.
11. According to Eurostat, the primary energy consumption was 1585 million toe in Europe in 2012. http://epp.eurostat.ec.europa.eu/portal/page/portal/europe_2020_indicators/headline_indicators/statistical_dashboards/climate_change_energy/primary_energy.

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Appendix

Table A1. Determination of the suitability values per class for each biophysical variable assigned to energy crop types.

		Energy crops – suitability-level values							
Biophysical variables	Classes	MSC	SWG	RC	GR	CD	WL	PL	EUC
Soil pH	0–4	NS	NS	NS	NS	NS	NS	NS	NS
	4–5	LS	LS	LS	PS	PS	PS	PS	PS
	5–6	S	MS	MS	S	MS	MS	MS	MS
	6–7	VS	VS	VS	VS	VS	VS	VS	VS
	7–8	MS	LS	S	MS	S	S	S	S
LGP (days)	0	NS	NS	NS	NS	NS	NS	NS	NS
	1–59	NS	NS	NS	NS	NS	NS	NS	NS
	60–149	VS	VS	VS	VS	VS	NS	NS	NS
	150–209	VS	VS	VS	VS	VS	VS	VS	VS
	210–269	VS	VS	VS	VS	VS	VS	VS	VS
	270–365	VS	VS	VS	VS	VS	VS	VS	VS
FFD	0–100 frost-free days	NS	NS	NS	NS	NS	NS	NS	NS
	100–200 frost-free days	S	S	S	NS	S	NS	NS	NS
	200–300 frost-free days	S	S	VS	S	VS	VS	VS	VS
	>300	VS	VS	VS	VS	VS	VS	VS	VS
Soil texture*	Coarse	MS	MS	PS	MS	LS	LS	MS	MS
	Medium	S	VS	VS	VS	VS	VS	VS	VS
	Medium fine	VS	VS	VS	VS	VS	VS	VS	VS
	Fine	LS	MS	MS	S	MS	MS	LS	MS
	Very fine	PS	NS	PS	MS	NS	NS	NS	MS
	No mineral soils	NS	NS	NS	NS	NS	NS	NS	NS

(*Continued*)

Table A1. (Continued).

Biophysical variables	Classes	Energy crops – suitability-level values MSC	SWG	RC	GR	CD	WL	PL	EUC
Soil depth (cm)	<10, lithic	NS	NS	NS	NS	NS	NS	NS	NS
	10–20, shallow	NS	NS	NS	NS	NS	NS	NS	NS
	20–40, shallow	NS	NS	PS	NS	NS	NS	NS	NS
	40–60	PS	PS	LS	NS	PS	NS	LS	LS
	60–80	MS	MS	MS	MS	MS	MS	MS	MS
	80–100	MS	MS	S	S	MS	MS	MS	MS
	100–120	S	S	VS	VS	S	S	S	S
	120–150	VS	VS	VS	VS	VS	VS	VS	VS
Soil type	Alluvial deposits	S	S	S	S	S	S	S	S
	Other rocks	NS	NS	NS	NS	NS	NS	NS	NS
	Sandy materials	VS	VS	VS	VS	VS	VS	VS	VS
	Clayey materials	VS	VS	VS	VS	VS	VS	VS	VS
	Crystalline rocks	LS	LS	LS	LS	LS	LS	LS	LS
	Volcanic rocks	NS	NS	NS	NS	NS	NS	NS	NS
	Loamy materials	VS	VS	VS	VS	VS	VS	VS	VS
	Calcareous rocks	MS	MS	S	MS	MS	MS	MS	MS
	Detrital formations	MS	MS	MS	MS	MS	MS	MS	MS
Soil drainage	Excessively well drained	VS	VS	VS	VS	VS	VS	VS	VS
	Imperfectly drained	NS	NS	NS	NS	NS	LS	NS	NS
	Moderately drained	MS	MS	MS	S	MS	MS	MS	MS
	Poor drained	NS	NS	NS	NS	NS	LS	PS	NS
	Temporary drained	LS	LS	LS	LS	LS	LS	LS	LS
	Very Poor drained	NS	NS	NS	NS	NS	NS	NS	NS
	Well drained	S	S	S	S	S	S	S	S
Temperature (°C)	<−15	NS	NS	NS	LS	NS	NS	LS	NS
	0–4	NS	NS	NS	MS	NS	NS	LS	NS
	4–6	PS	PS	NS	MS	NS	PS	MS	NS
	6–8	VS	MS	NS	MS	NS	S	VS	NS
	8–10	VS	VS	PS	S	PS	VS	VS	PS
	10–15	VS	VS	VS	VS	VS	VS	VS	VS
	15–20	PS	PS	VS	LS	VS	LS	LS	VS
	>20	NS	NS	VS	LS	VS	NS	PS	VS
Precipitation (mm)	0–200	NS	NS	NS	NS	NS	NS	NS	NS
	200–400	NS	NS	MS	NS	LS	NS	NS	LS
	400–500	NS	MS	MS	LS	MS	NS	NS	MS
	500–600	LS	MS	MS	MS	MS	MS	NS	MS
	600–800	MS	S	S	S	S	S	S	S
	800–1000	S	VS	VS	VS	VS	VS	VS	VS
	>1000	VS	VS	VS	VS	VS	VS	VS	VS
Slope (%)	0–2	VS	VS	VS	VS	VS	VS	VS	VS
	2–5	S	S	S	S	S	S	S	S
	5–8	MS	MS	MS	MS	MS	MS	MS	MS
	8–16	LS	LS	LS	LS	LS	LS	LS	LS
	16–30	PS	PS	PS	PS	PS	PS	PS	PS
	>30	NS	NS	NS	NS	NS	NS	NS	NS

Notes: VS, very suitable (score assigned = 5); S, suitable (score assigned = 4); MS, moderately suitable (score assigned = 3); LS, low suitability (score assigned = 2); PS, poorly suitable (score assigned = 1); NS, not suitable (score assigned = 0); MSC, miscanthus; SWG, switchgrass; RD, reed canary; GR, giant reed: CD, cardoon: WL, willow: PL, poplar; EUC, eucalyptus.

**Coarse: 18% < clay and >65% sand; medium: 18% < clay < 35% and 15% sand; medium fine: <35% clay and <15% sand; fine: 35% < clay < 60%; very fine: clay > 60%; no mineral soils: peat soils.