A GIS-based approach to evaluate biomass potential from energy crops at regional scale

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ABSTRACT

The aim of the paper is to propose a method to maximize energy production from arboreous and herbaceous dedicated crops given the characteristics of the local environment: geo-morphology, climate, natural heritage, current land use. The best energy crops available in the Italian panorama are identified and the problem of maximizing the bioenergy production over an entire regional area is formulated. Each cultivar is thus assigned to the suitable land accounting for sensitive parameters that characterize it and taking into account current land use. The assumption made here is that marginal land and set-asides can be converted to energy crops without altering current practices and cash crops’ production. The method is based on the integration of GIS data (spatially continuous) with data derived from the agricultural census (spatially discrete). We carry out the analysis for Emilia-Romagna, in Northern Italy. The sustainable growth of energy crops, with an optimized network of conversion facilities distributed in the territory, may significantly contribute to the local energy supply and to climate change mitigation.

1. Introduction

The farming of arboreous and herbaceous species to produce biomass for energy purposes is a major theme of debate in energy planning: Google Scholar (April 2009) lists over 24,000 papers containing the words “biomass, energy, agriculture” published since 2000. Biomass is certainly not the final answer to the energy issue, nor to carbon mitigation policies (Righelato and Spracklen, 2007). It can but it can contribute to broaden the energy portfolio, allowing for: distributed production systems; use of by-products and residues that would otherwise be wasted; re-allocation of unused agricultural land with positive social impacts.

Globally, biomasses are the most important renewable energy source supplying about 11% of the primary energy, whereas hydropower supplies 2.2% and other resources (geothermal, wind, solar) only 0.5% (IEA, 2005). These figures are completely different in industrialized countries, where only 3.3% of primary energy derives from biomass (IEA, 2005).

Figures for future objectives are, though, ambitious. In 2010, the EU25 target set in the Biomass Action Plan is the production of 6.3 EJ (1 EJ = 10^18 J) from bioenergy; in 2005, production amounted to 3.0 EJ divided in solid biomass (80%), biogas (7%), biofuels (5%) and renewable municipal solid waste (8%) (EuroObserv’ER, 2006). Regarding greenhouse gases (GHG), under the Kyoto Protocol, the European Community, which at that time had 15 Member States, agreed to reduce emissions by 8% from 1990 base year levels by 2008–2012, a reduction of about 330 million tonnes of CO2 equivalent. However, it will be difficult to meet such a commitment: GHG emissions decreased just by 2.0% in 2005 compared to the base year. Italy, in particular, is far from meeting Kyoto targets (6.5% reduction with respect to 1990); in fact in 2005 emissions increased by 12% compared to the base year (EEA, 2007).

Energy crops are intensive cultivations characterised by high plant densities and mechanisation, short rotation (from 1 to 4 years) and plant cycles (less than 20 years), that can help in substituting conventional fossil fuels and avoid the emissions of significant amounts of GHG.

Most of the literature focuses on woody species grown in short rotation forestry (SRF) such as poplar, willows, eucalyptus and robinia (Karačić and Weiβ, 2006; Mitchell et al., 1999; Volk et al., 2006). Recently, attention has been increasing towards herbaceous species, such as sorghum, which differ from SRF mainly because they are annual crops (Clifton-Brown et al., 2004; Sims et al., 2006; Venturi et al., 1999). Over the year, annual bioenergy crops have a growing cycle similar to that of traditional food crops: they can substitute the latter more easily, since the farmer does not have to
commit his/her land for a long period and each year a decision can be taken on what crop to grow depending on the demand (e.g., corn or sorghum). Research is also focused on other herbaceous species such as switchgrass (*Panicum virgatum L.*) and miscanthus (*Miscanthus × giganteus*). These are two C4 rhizomatous perennial grasses capable of high yields under good conditions, especially when water and nitrogen are largely available (Ercoli et al., 1999; Heaton et al., 2004). Once planted, perennials can be harvested every year for an overall cycle, as for SRF, of 15–20 years (Venturi et al., 1999). Recently, a new vision for energy crops was given by Tilman et al. (2006) who proposed to re-establish native mixed prairie grasses in the Northern USA plains both to produce high yields of biomass with low inputs and to exploit their potential to sequester carbon in roots and soil.

Most current literature is devoted to experimental or theoretical evaluations of the best crop for a given land (Bazzani et al., 2005; Di Virgilio et al., 2007; Ercoli et al., 1999; Facciotto et al., 2006; Karačić and Weih, 2006); to economic and environmental assessments of a certain crop (Heller et al., 2003; Monti et al., 2007); to the analysis of the energy budget of a single existing or projected conversion plant (Goor et al., 2000). As noted by Wise et al. (2007), carbon sink plans should be developed at least at a district level, and in fact we take here the point of view of a regional authority that has to plan for the development of a biomass sector to understand if it can play a significant role as an energy provider and as an effective GHG mitigation policy. Such an analysis can only be performed by a GIS based method that considers the spatial distribution of both the availability and the utilization of biomass. A regional or national planning approach has been used in few studies. Schneider et al. (2001) propose a GIS approach to assess land availability in Brazil. Fischer et al. (2005) are developing a method to define environmental requirements for crop and forest tree species, where climate, soil and terrain features are based on GIS. De la Rosa et al. (2004) developed a model to support agro-ecological decisions for soil protection, integrating land planning and management with current land use.

The proposed method aggregates information coming from different data sets, organized in different format: digitized cartography for soil characteristics, qualitative descriptions of cultivar agronomic needs, and numerical data for land use. The method is analysed in detail in the following section. We show how to assess the site and the extension of land to be dedicated to energy crops, considering both woody and herbaceous species, and propose a method to manage a sustainable biomass-to-energy system at regional scale (Section 3). The assessment of energy crops’ productivity comes along with the analysis of GHG flows: an emissive analysis is conducted in Section 4 for each considered species. The suggested approach is very general and can be used whatever the type of crops under considerations and whatever the type of utilization foreseen (e.g., production of biofuels or bio-alcohols, of electric power, of thermal energy or co-generation). Here, the method is applied to Emilia-Romagna region (Section 5), a large agricultural area in Northern Italy, where the foreseen utilization is combustion for thermal or electrical energy production.

2. The proposed procedure

Land that can be dedicated to energy crops is identified at local scale through detailed cartography and datasets, considering morphological, pedological and climatic characteristics, administrative borders and current land use. More precisely, as Fig. 1 shows, our work is organized as follows:

1. **Species selection:** agronomic needs must be defined for each considered crop (phytologic database)

2. **Land suitability:** data are necessary to describe soil characteristics and, thus, to understand where each kind of crop can be grown according to its agronomic needs (cartography)

3. **Land availability:** since not all the suitable land can be converted to energy crops, available land must be identified with the help of current land use data (statistical database) and taking into account political and social constraints

4. **Land assignment/plant location:** a decision process must be defined in order to determine which crop to grow in each parcel of suitable land available and where to exploit its energy.

The first step (species selection) consists in identifying promising crops for the area under investigation and the related phytologic characteristics. This means that a database of soil, climatic and geo-morphological preferences for each crop is needed, together with information about the nature and extent of the agricultural activities required by each investigated crop.

The second step is to organize a database of cartographic information (land suitability) of the studied area. This database should contain data on morphology, soil pedology, climate and all other features that evaluate the suitability of the area to cultivation of the selected species. All these information are normally available as digital cartography, allowing for a continuous representation of data. With the help of GIS tools, all the area is subdivided into parcels (minimum units with uniform attributes, as in Tianhong et al., 2003) that meet one or more of the criteria for the cultivation of the bioenergy crops. A parcel of land can in fact be suitable for one or more species, thus a decision will necessarily be made on which crop to chose.

Using statistical data on the agricultural activities of each parcel, as well as information on the areas with legal restrictions (such as natural parks), the third step is to deduce the availability of suitable land in each parcel for each crop (land availability). This step implies a number of political choices, and specifically the extent to which current agricultural practices may be modified. This would require a careful comparison of the benefits from current agriculture with respect to the possible gains from energy crops. However, it must be noted that a complete formulation of an agricultural plan (including all food and non-food crops, their agricultural practices, land suitability, transportation and utilization costs, etc.) may become very complex (e.g., the model developed by De La Torre Ugarte et al., 2003) and, more important, its solution may be too far from the current situation and thus may result unacceptable. This is why we prefer to fix a priori some limits to the plan, in order to guarantee its social acceptability. In the case study that we present in Section 5, for instance, the decision taken allows energy crop cultivation only on land which is not currently used for food agriculture, thus only minimally perturbing existing practices.

The fourth step consists in deciding which species to grow in each suitable and available area (land assignment). When more than one crop can be grown on a certain soil, an optimization problem needs to be solved. We assume that the objective of such a problem is the maximization of the energy produced. This requires the computation of the energy output from biomass utilization, which means, in turn, that one has to select type, size and location of conversion plants (plant location).

3. The energy maximization problem

The land assignment/plant location optimization problem can be formulated accounting for the net energy produced in the system given by the energy plants’ output (that depends on number, size and efficiency of the plants) subtracted the energy needed to transport biomass from fields to plants (that depends on
plant location and on collection basins) and the energy needed to grow and harvest energy crops.

We assume as decision variables: \( x_{ijk} \), the area, in hectare (ha), in parcel \( i \)-th, grown with species \( k \)-th and hauled to plant \( j \)-th at a distance \( d_{ij} \), and \( y_j \), a binary variable indicating if the plant is built in parcel \( j \) (\( y_j = 1 \)) or not (\( y_j = 0 \)).

The net energy production, to be maximized, is thus

\[
\max \sum \sum \sum \left[ (\eta_j \cdot LHV_k \cdot u_k \cdot x_{ijk}) - (e_{\text{transport}} \cdot d_{ij} \cdot u_k \cdot x_{ijk}) - (e_{\text{grow}} \cdot x_{ijk}) \right] \quad (1)
\]

where:

- \( u_k \) is the annual biomass yield of the \( k \)-th species, in dry tons/ha. It does not depend on the specific land parcel \( i \), since only the most suitable land for growing crop \( k \) has been selected in the previous steps.
- \( \eta_j \) is the \( j \)-th plant efficiency.
- \( LHV_k \) is the lower heating value of the \( k \)-th species, in MJ/dry ton.
- \( e_{\text{transport}} \) is the annual energy cost, in MJ/dry ton/km, for hauling a unit of biomass over a unit of distance, return trip included.
- \( e_{\text{grow}} \) is the annual energy cost, in MJ/dry ton, for growing biomass, again assumed to depend only on the species \( k \).

The objective function is subject to the following constraints:

\[
\sum_{j} \sum_{k} x_{ijk} \leq A_i \quad \forall \ i \quad (2)
\]

It imposes that the sum of areas \( x_{ijk} \) cultivated with crop \( k \) in parcel \( i \) must be at the most as big as the available land \( A_i \) (in ha) in the same parcel, identified in the previous steps of the procedure.

\[
\sum_{i} \sum_{k} LHV_k \cdot u_k \cdot x_{ijk} \leq CAP_j \cdot \xi^H \cdot y_j \quad \forall \ j \quad (3)
\]

It limits the supply to each plant in a range, defined by a lower \( \xi^L \) and an upper \( \xi^H \) bound of the nominal production capacity \( CAP_j \) (in MJ/y), when the plant is actually built in location \( j \) (\( y_j = 1 \)), and sets the supply to zero otherwise (\( y_j = 0 \)). Working around the nominal capacity of the plant, guarantees that the value \( \eta_j \) of the conversion efficiency is indeed meaningful and prevents from defining very small plants that may be unjustified from the economical viewpoint.

\[
x_{ijk} \geq 0, \quad y_j = 0, 1 \quad \forall \ i, j, k \quad (4)
\]
GHG emissions, as listed in Table 3. Fertilizer are applied after establishment (120 kg/ha N, P, K for LI and HI crops and for sorghum) and after harvesting (60 kg/ha N, P, K for LI crops; 300 kg/ha N, 250 kg/ha P, K for HI crops). Emissions from fertilizers are due both to energy requirements for their production and to N₂O emissions after application, with an emission factor of 1.25% of N₂O per nitrogen applied (IPCC, 1997), even though this is a controversial figure (e.g., Crutzen et al., 2008). Plant protection products (0.3 kg/ha) and herbicides (0.45 kg/ha) are also applied; we took into account the emissions in Table 3 due to the energy required for their production.

As already pointed out, land assignment has two types of constraints: an environmental one that may be considered continuous on the territory and thus may be computed using GIS procedures, and a social one, that entails the definition of which portion of suitable land may be devoted to energy crops. The latter implies that decisions at the level of each parcel shall be taken; thus, it can be elaborated only using statistical data which are in a way discrete, since they refer to each parcel.

3.2. Land suitability

The specific soil requirements of each species are defined in terms of:

- geo-morphological variables: slope, altitude;
- pedological variables: geotechnical (soil texture and depth, presence of gravels, stability, drainage) and soil (pH, presence of limestone) characteristics;
- climatic variables: temperature and precipitation regimes;
- physical–chemical variables: presence of elements such as organic carbon, nitrogen, carbon to nitrogen ratio, phosphorus and calcium.

All these variables may be represented on the digital cartography of the region to show where the environmental conditions are suitable for each species. Subtracting areas unusable for prescriptive reasons (e.g., natural parks, preservation zones), one obtains an estimation of the surface that is suitable for farming energy crops (and obviously also of the surface where cultivation is infeasible). It will certainly happen that, for many parcels, more than one crop is suitable; the decision over which crop to choose will be made in the last step of the procedure.

Parcels which turn out to be less than a given minimum surface may be excluded from further processing (SRF require machinery and personnel start-up costs that cannot be justified for very small surfaces). Finally, it is often useful, for instance, to guarantee compatibility with the administrative statistics, to impose that each parcel completely lies within the border of an administrative unit. This simply requires the additional intersection with the layer of administrative borders and splits the areas of equal land characteristics lying across the borders into separate parcels each included only in one administrative unit.

3.3. Land availability

An additional crucial point is to understand what kind of land can be grown or replaced with energy crops without negatively affecting the food market, as recently experienced by Mexico and USA, which witnessed a substantial increase in maize prices driven by the increased demand of corn to produce biofuels (The Economist, 2007). This means that a constraint considering the socio-economic conditions of the studied areas must be set.

For example, it can be decided to convert a given portion of the land currently dedicated to cash crops. In Italy (as in other EU countries) food agriculture has an extremely long tradition, even if to date farmers income relies largely on subsidies, due to the import of cheaper goods and to the overproduction of traditional food crops. Moreover, farmers were paid (with the new EU Agricultural Policy this subsidy has been cancelled) not to grow food crops. Moreover, farmers were paid (with the new EU Agri-cultural Policy this subsidy has been cancelled) not to grow food crops on a given percentage of their arable land (the so-called set-aside).

In this study, we will assume not to alter the current land use and thus to dedicate to energy crops only agricultural marginal land and set-aside land. This defines, in each parcel i, the available land A_i which is used in constraint (2). Clearly, any percentage of presently cultivated land may be devoted to energy crops, but an economic analysis of such an alternative should, as already mentioned, take into account the missed benefits from the pre-existent food crops.

3.4. Land assignment

As already anticipated, this problem can be split into two parts, thanks to the following considerations.

The objective function (1) can be rewritten as a linear function of the biomass produced u_k \cdot x_{ijk}, i.e.

$$
\max \sum_{i} \sum_{j} \sum_{k} \left[ (\eta_j \cdot LHV_k) \cdot (\eta_{\text{transport}} \cdot d_{ij}) - \eta_{\text{grow}} \cdot u_k \cdot x_{ijk} \right]
$$

(5)
The hauling distance $d_{ij}$ is the only link between power production and plant location. If we assume to fix it to a maximum value $d^*$ (in Italy, for instance, there are incentives to keep this value below 70 km), the objective function (5) can be reduced to

$$
\max \{ x_{ij} \} \quad J = \sum \sum \sum \alpha_k u_k x_{ijk} \quad (6)
$$

where the coefficients $\alpha_k$ may be positive or not, and the only remaining constraints are on land availability (2) and non-negativity of decision variables (4). This objective function is obviously maximized by setting the addenda to the highest possible value. If $\alpha_k$ is negative, the solution is clearly not to grow any crop in parcel $i$. On the contrary, if $\alpha_k$ is positive, this means fixing $x_{ijk}$ to the total area available in the parcel (thus satisfying constraint (2) above) and select the type of crop (i.e. the value of $k$), with the highest net energy yield $\alpha_k u_k$.

We note that a crop having a higher yield for a distance $d^*$, is also preferable for all shorter distances, since the energy for transportation would just decrease for all crops. This allows to conclude that, whatever the number and location of plants, energy is maximized by assigning the land to the most efficient crops with a simple "greedy" approach. Parcels where only one crop $k$ is possible must be cultivated with that crop, whereas the most productive crop is assigned to the parcels where more than one is suitable. Clearly, for each parcel $i$, only one value of $k$ is selected: i.e. the available land in each parcel is a monoculture (though its production may be assigned to more than one plant $j$ or discarded when solving the plant location problem). Note additionally that $\alpha_k$ has a weak dependence on $k$ when possible crops have quite different yields, but similar heating and energy cultivation values (see, for instance, Tables 1 and 2). In this common situation, the crop with the highest biomass production per hectare $u_k$ is assigned to each parcel.

3.5. Plant location

A classical plant location problem can now be solved with the biomass available in each parcel determined above. At this stage, the correct energy balances are computed, accounting for the actual distances over which the crops are hauled.

The energy maximization can in fact be formulated with the decision variables $x_{ij}$ and $y_j$. Note that the dependence on $k$ has been cancelled, since each parcel $i$ has now been assigned a specific crop:

$$
\max \{ x_{ij} \} \quad J = \sum \sum \left( \eta_j LHV_j u_i x_{ij} - (e_{\text{transport}} d_{ij} u_i x_{ij}) - (e_{\text{grow}} u_i x_{ij}) \right) \quad (7)
$$

Constraints (2)–(4) are similarly modified:

$$
\sum \sum x_{ijk} \leq A_i \forall \ i \quad (8)
$$

$$
CAP_j \cdot \frac{1}{e} y_j \leq \sum \sum LHV_k u_k x_{ijk} \leq CAP_j \cdot \frac{1}{e} y_j \forall \ j \quad (9)
$$

$$
x_{ij} \geq 0, \quad y_j = 0, 1 \forall i, j \quad (10)
$$

This is a standard problem that can be solved as described in the literature (e.g., Drezner and Hamacher, 2001). It must include the specific features of both the territory and the transformation plants. For instance, parcels candidate to house a plant should have enough land available for its installation. Moreover, if district heating is provided, the parcel where the plant is located should contain a town big and densely populated enough to efficiently exploit the heat supplied by the plant.

The solution may include parcels where $x_{ij}$ is zero for all $j$, if they have a negative energy balance, even when cultivated with the best crop, or if their production is insufficient to justify the construction of an additional plant.

Under the assumptions above, the decoupling procedure used to solve the problem has been tested to determine the same optimum of the whole problem stated in eqs. (1)–(4), in one-fifth of the time in the case study described later.

4. Greenhouse gases flows

Together with the assessment of biomass availability, it is crucial to estimate how energy crops contribute to the reduction of GHG. In the analysis, both direct (fuel consumption in the machinery) and indirect (fertilizer production) emissions have been considered. Flows are expressed in terms of t CO2eq/ha/y in order to allow for a comparison between the different crops and to consider CO2, N2O and CH4 emissions (respectively, with a global warming potential of 296 and 23 over 100 years relative to that of CO2; Forster et al., 2007).

Emissions are associated with the following activities (Table 3): crop establishment, fertilizer production, machinery operations (fertilizer application, weeding, irrigation, harvesting and removal of timber from the site, re-establishment of the site). Transport emissions are assumed to differ over short (less than 10 km) and long (over 10 km) distances, due to different conveyance means. Sequestration (t CO2eq/ha/y) is associated with above and below ground biomass and with soil. Annual carbon sequestration varies, according to the species considered, from 15 to 43 t CO2eq/ha (Table 4).

Emissions associated with crop cultivation and transportation to the transformation site are just a small share of carbon sequestered by energy crops. High input SRF have higher potential than low input because the increased carbon sequestration overcomes the increase of emissions associated with the higher energy needs of the crop. Sorghum has the best performance because its high

Table 3

<table>
<thead>
<tr>
<th>Farming operations</th>
<th>Diesel consumption (MJ/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ploughing</td>
<td>1908</td>
</tr>
<tr>
<td>Harrowing</td>
<td>1080</td>
</tr>
<tr>
<td>Planting as cuttings</td>
<td>540</td>
</tr>
<tr>
<td>Sowing</td>
<td>504</td>
</tr>
<tr>
<td>Applying chemical weed control</td>
<td>720</td>
</tr>
<tr>
<td>Applying mechanical weed control</td>
<td>540</td>
</tr>
<tr>
<td>Applying plant protection products</td>
<td>540</td>
</tr>
<tr>
<td>Fertilizing (N, P, K)</td>
<td>540</td>
</tr>
<tr>
<td>Irrigation</td>
<td>6912</td>
</tr>
<tr>
<td>Harvesting</td>
<td>4320</td>
</tr>
<tr>
<td>Crop removal</td>
<td>1800</td>
</tr>
<tr>
<td><strong>Hauling</strong></td>
<td></td>
</tr>
<tr>
<td>Short distances (&lt;10 km)</td>
<td>594</td>
</tr>
<tr>
<td>Long distances (≥10 km)</td>
<td>1060</td>
</tr>
<tr>
<td><strong>Fertilizers</strong></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>73.7</td>
</tr>
<tr>
<td>P</td>
<td>13.4</td>
</tr>
<tr>
<td>K</td>
<td>9.2</td>
</tr>
<tr>
<td><strong>Pests and weeds control</strong></td>
<td></td>
</tr>
<tr>
<td>Energy requirement for production</td>
<td></td>
</tr>
<tr>
<td>(MJ/kg)</td>
<td></td>
</tr>
<tr>
<td>Weed control products</td>
<td>91</td>
</tr>
<tr>
<td>Plant protection products</td>
<td>53</td>
</tr>
</tbody>
</table>
density and annual rotation lead to higher biomass yields, which means higher CO₂ sequestration.

5. Case study: Emilia-Romagna

The area of analysis is the Emilia-Romagna region (Fig. 2), located in Northern Italy. Emilia-Romagna has an extension of about 22,123 km², 7.3% of the area of Italy. The region is divided in 341 municipalities; the average municipality area is about 65 km². Almost half of the regional territory is in the river Po valley (48%), a fertile and highly cultivated plain; the remaining is divided between hills (27%) and Apennine mountains (25%). The agricultural land amounts to about 14,500 km², 76% of this is currently cultivated (ISTAT, 2000); details on the agricultural land use are given in Table 5. The main cash crops are wheat and maize. Moving uphill, the incidence of crop land decreases in favour of woods (which account for 23% of the regional territory), marginal and abandoned land.

5.1. Bioenergy crops potential given current land use

In order to assess the suitable land for energy crops cultivation, the following spatial data were gathered from digitized regional cartography (Fig. 1): pedological (1:250,000), phytoclimatic (1:500,000) and land use (1:25,000) cartographies. Unsuitable area for any energy crops in Emilia-Romagna was defined as the land satisfying one or more of the following constraints:

- altitude above 750 m;
- high slope (more than 20%);
- soil containing rocks, gravels, pebbles;
- thin upper layer (not deep enough for root development);
- soil pH lower than 5.0 or higher than 8.5;
- average annual precipitation below 700 mm/y and average temperature below 10 °C or above 15 °C;
- protected natural areas.

Land suitable for energy crops in Emilia-Romagna is shown in Fig. 3. Overall, it accounts for 9701 km² (about 44% of the regional area), the remaining area (white on the map) being excluded because of one or more of the above constraints.

Only a small portion of the land which fits the requirements of energy crops (SRF or sorghum), is actually available because of the current land use in Emilia-Romagna. We assume to convert to SRF all the marginal land, that is abandoned agricultural land, and to sorghum, an annual crop, all the set-aside land. Set-aside land may

Table 4
Carbon equivalent flows for the energy crops considered (poplar clones I-214 and BL Costanzo are subject to the same agricultural operations).

<table>
<thead>
<tr>
<th>Species</th>
<th>Sequestration (t CO₂eq/ha/y)</th>
<th>Farming (t CO₂eq/ha/y)</th>
<th>Transport &lt; 10 km (t CO₂eq/ha/km/y)</th>
<th>Transport ≥ 10 km (t CO₂eq/ha/km/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-214/BL C LI</td>
<td>16.13</td>
<td>0.59</td>
<td>2.16 x 10⁻⁴</td>
<td>3.85 x 10⁻⁴</td>
</tr>
<tr>
<td>I-214/BL C HI</td>
<td>24.93</td>
<td>3.56</td>
<td>3.39 x 10⁻⁴</td>
<td>6.06 x 10⁻⁴</td>
</tr>
<tr>
<td>Lux LI</td>
<td>21.01</td>
<td>0.59</td>
<td>2.65 x 10⁻⁴</td>
<td>4.74 x 10⁻⁴</td>
</tr>
<tr>
<td>Lux HI</td>
<td>30.28</td>
<td>3.56</td>
<td>3.85 x 10⁻⁴</td>
<td>6.88 x 10⁻⁴</td>
</tr>
<tr>
<td>Robinia</td>
<td>21.26</td>
<td>0.46</td>
<td>2.44 x 10⁻⁴</td>
<td>4.35 x 10⁻⁴</td>
</tr>
<tr>
<td>Willow</td>
<td>22.24</td>
<td>1.06</td>
<td>3.15 x 10⁻⁴</td>
<td>5.62 x 10⁻⁴</td>
</tr>
<tr>
<td>Sorghum</td>
<td>52.80</td>
<td>8.97</td>
<td>7.40 x 10⁻⁴</td>
<td>13.2 x 10⁻⁴</td>
</tr>
</tbody>
</table>

Fig. 2. Map of Emilia-Romagna land use (Regione Emilia-Romagna, 2003).
rotate every agricultural and so the annual timing of sorghum is in phase with land availability. On the other hand, abandoned and marginal land supposedly remains in the same condition for a longer lapse of time and, therefore, may be dedicated to a crop with 14–15 years duration. Information on land use at such a detail (agricultural marginal land and set-aside) are not available on cartographic support, neither it will be available in the future since set-aside areas enter the annual crop rotation and thus move year by year. We thus consider the national agriculture database (ISTAT, 2000) that provides data (extensions) on land uses for each municipality of the region (Fig. 1).

In order to merge the cartographic continuous information and the statistical discrete data, we proceed as follows: for each parcel in the h-th municipality, we scale the amount of suitable land for each crop to the area of the municipality whose current land use is “non-utilized land” (in the case of arboreal crops) or “set-aside land” (in the case of sorghum). This approximation implies that the fraction of non-utilized or set-aside land is the same in all the parcels of the same municipality, but it is quite reasonable because most of the suitable land is in the river Po valley (Fig. 3) where the quality of agricultural land is almost uniform in each municipality. Such an operation can be synthesized, for each parcel, with the following simple formula:

$$A_{hi} = S_h \cdot \frac{M_{hi}}{L_h}$$

(11)

where

- $A_{hi}$ is the available land of type l (non-utilized or set-aside) in a parcel of the h-th municipality;
- $S_h$ is the surface area of the parcel;
- $M_{hi}$ is the marginal or set-aside land (depending on l) of the h-th municipality;
- $L_h$ is the total agricultural land in the h-th municipality.

In Emilia-Romagna, available land for energy crops turns out to be 11,300 ha for SRF (marginal land) and to 18,300 ha for sorghum (set-aside); together these account for 1.3% of the regional area.

Given the available land, it is now possible to proceed to the solution of the problem. Dealing with its complete formulation would mean tackling a fairly large problem. In our case study, the set of possible crops contains 6 species, three of which can be grown according to two farming practices, thus we can choose between 9 alternatives. We could assume that the parcels coincide with the municipalities of Emilia-Romagna (341) and that the plants can be located in all municipalities. Therefore, a blind implementation of Eq. (1) would lead to a problem where the number of decision variables is as high as $9 \times 341 \times 341$ plus 341 binary variables $y_j$. With the proposed approach, we decouple the problem by assigning the most rewarding species $k$ to each parcel $i$, and then by solving the location/allocation problem; by doing so we substantially reduce the number of variables. The solution obtained by the proposed procedure is the same as that of the complete MIP problem, as anticipated in Section 3.5, by simply assigning to each parcel the crop with the highest biomass yield, since the values of LHV and energy required for farming are very similar for each species $k$, and the only significant difference is thus the crop yield (Table 1).

The result of the land assignment step indicates that farming the available marginal land with SRF may yield about 150 kt of dry biomass per year, together with 410 kt of dry sorghum per year grown on set-aside land. Their contribution to the regional energy and GHG budgets clearly depends on the technology adopted for the final energy conversion and on the resolution of the location problem.

### 5.2. Contribution to climate change mitigation

We assume that the biomass will fuel co-generation plants of a maximum size of 5 MWe, which corresponds to the suggested maximum size for these kind of plants in Italy (Brignoli et al., 2004). Their electrical efficiency is 17%, whilst the thermal efficiency is 80%. Several similar plants are indeed functioning in Europe. Moreover, in Italy several regional administrations are promoting the development of such biomass co-generation plants by allowing the construction not only in industrial areas, but in rural areas as well (e.g., Regione Lombardia). In fact, a higher size would produce an amount of heat that would hardly find a comparable market.

The solution of the optimization problem results in the construction of 13 such plants, with the location sites and collection basins represented in Fig. 4. It is possible to observe that the plants are located close to the most important route of the region (Via Emilia); the biggest towns, where district heating is more advantageous, are located along this road as well.

The sensitivity of the objective value with respect to locations and collection basins of the plants is small; in fact, if we move the sites to nearby municipalities or modify the collection basins, the values of the objective are subject to small changes. This is due to the fact that the energy required for transportation is less than 1% of the energy produced. If the assumed conversion technology is adopted, the actual siting decision will probably be driven by issues such as, for example, thermal energy demand or impacts on the landscape, rather than by the optimization of the regional objective.

The amount of GHG emissions avoided is estimated with respect to the production of the same amount of energy from natural gas, that has an emission factor of 56.6 t CO$_2$/TJ (vs. 93 for coal and 74 for crude oil; Herold, 2003); we assumed a gas co-generation plant with 38% electrical efficiency and 80% heating efficiency (average values of the Italian installed base). Under these assumptions, about 440 kt of CO$_2$ would be avoided thanks to the substitution of natural gas with biomass. The farming of energy crops would cause the emissions of about 172 kt CO$_2$ eq and the transportation of biomass from the production to the conversions facilities would emit 1.2 kt CO$_2$ eq. The optimal configuration of these plants would thus reduce the emissions of the Region by about 267 kt CO$_2$ eq. This figure corresponds to the 0.7% of 2003 regional carbon dioxide emissions (Regione Emilia-Romagna, 2007), but represents 3.2% of the emissions from the energy sector (8,331 kt CO$_2$).

Energy crops can provide 1.3% of the electrical energy demand in Emilia-Romagna (29.389 GWh in 2007, 12.9% of which are satisfied through import) and reduce the regional deficit by 12.3% (Terna, 2008). As for thermal energy, in 2004 about 800 GWh of thermal energy were supplied by co-generation plants fuelled for 95% with

### Table 5

Agricultural land use in Emilia-Romagna [ISTAT, 2000].

<table>
<thead>
<tr>
<th>Areas (km$^2$)</th>
<th>Areas (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilized agricultural land</td>
<td>11154</td>
</tr>
<tr>
<td>Arable land</td>
<td>8185</td>
</tr>
<tr>
<td>Set-aside</td>
<td>317</td>
</tr>
<tr>
<td>Fruit trees</td>
<td>1511</td>
</tr>
<tr>
<td>Family gardens</td>
<td>13</td>
</tr>
<tr>
<td>Pastures</td>
<td>1127</td>
</tr>
<tr>
<td>Productive woods</td>
<td>2112</td>
</tr>
<tr>
<td>Non-utilized agricultural land</td>
<td>423</td>
</tr>
<tr>
<td>Others</td>
<td>984</td>
</tr>
<tr>
<td>Total agricultural land</td>
<td>14672</td>
</tr>
</tbody>
</table>
fossil fuels. Energy crops can distribute through district heating enough heat to double the overall figure to 1600 GWh.

5.3. Economics of the proposed energy system

We performed a preliminary analysis of the economic balance of the co-generation plant network, assuming that energy crops are bought from the farmer at a price of 70 € per wet ton, that is the current price in the studied region (Cozzolino, 2008). The net present value for plants assuming a 7% interest rate, overnight construction costs, and 20 years of plant lifetime, is definitely positive and the payback time is less than 14 years. Accounting for green subsidies paid for electrical energy, it may become as low as 10 years.

As for the farmer, we estimated that the cost of biomass production, including all farming operations and land rent at 2006...
local prices, is 140 €/ton. This decreases to 50 – 80 €/ton if economic subsidies paid by various institutions are taken into account.

Even if incentives are available for both energy conversion and farming, green subsidies for electricity from renewable energies are higher (GSE, 2008) and are guaranteed by the electrical energy authority for 12–15 years, whilst subsidies for farming are funded by different administrations at European, national and regional level and have a typical timeframe of five years. This makes growing energy crops in Italy less economically rewarding than investing in conversion plants, which may explain why the expansion of this sector is so slow. Unifying all the stakeholders’ interests into district renewable energy associations may contribute to a more even distribution of the benefits and consequently open up faster developments.

6. Concluding remarks

We assume to devote to energy crops only optimal land where each species can find agronomic and phytoclimatic characteristics that best suits its need. Under these circumstances, energy crops will give their maximum yield. This is a conservative approach that limits the amount of biomass that can be grown in the studied region. Even land that is not optimal can be devoted to energy crops, but it will accordingly return yields lower than the maximum ones. Instead of having a yes/no (1/0) sharp assignment, the method could be extended by defining a land suitability function to set a value between one (optimal) and zero (unsuitable) to the productivity of each parcel of land with a given set of characteristics.

A concern about the proposed plan may be the foreseen reduction of biodiversity, which is in general a very important ecological issue. However, the amount of land involved in the proposed plan is very limited. The surface presently cultivated with wheat (the prevalent food crop) is about six times as much, and traditional food agriculture has been going on in the area since centuries. Furthermore, in the Rural Development Plan, the Emilia- Romagna regional government provided incentives to promote biodiversity in arboreal crops equal to 4800 €/ha. These incentives are supplied when three or more species are grown on the same parcel of land. Even though three species do not ensure biodiversity protection, this is the only incentive available to contrast monocultures. The analysis of this possibility involves adding to the original problem a constraint imposing that a minimum amount of land is assigned to each arboreal species in each suitable parcel. The solution of this problem shows a reduction of energy over the entire crop cycle due to the lower yields; this can be considered as the cost of practicing a more diverse bioenergy farming. However, it is amply repaid by the regional contribution.

Finally, it must be noted that the implementation of the proposed plan involves a consistent investment for the realization of the conversion plants (a rough estimation results in about 270 million euro, i.e. 0.3% of the annual regional gross product), but it will accordingly return yields lower than the maximum ones. This method could be extended by defining a land suitability function to set a value between one (optimal) and zero (unsuitable) to the productivity of each parcel of land with a given set of characteristics.

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