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(117) A GIS-BASED APPROACH FOR OPTIMIZING THE DEVELOPMENT OF COLLECTIVE BIOGAS PLANTS

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EXECUTIVE SUMMARY

Agriculture substantially contributes to anthropogenic emissions of both N_2O and CH_4 as well as ammonia (NH_3). As signatories to international conventions, EU Member States must reduce their emissions. Moreover, the European Council (December 12, 2008) defined the energy-climate package and implemented a target called "3 X 20". The aim of this target is to reduce GHG emissions by 20% by 2020 compared to 1990 levels. It also aims to bring to a 20% share of renewable energy in the final consumption and to increase energetic efficiency by 20%. In response to these commitments, anaerobic digestion of livestock wastes is expected to expand in France in the coming years. The objectives of economic performance lead to a particular interest in centralized treatment plants involving other wastes, specifically wastes with high potential for energy production (agri-food waste, crop residues, etc.) which may be collected over long distances. However, such development is complex and requires the awareness of social and technical constraints (heat recovery, access to bio-resources...) as well as adhering to legal restrictions in the concerned areas. In this context of potential development of collective biogas plants in France, the use of Geographic Information Systems (GIS) in order to georeference the bio-resources and then to locate the optimal sites appears very interesting and useful tools. Such investigations have been carried out on both national and regional scales (Batzias, 2005; Dagnall, 2010) but need to be adapted for local diagnosis. For this purpose, a research project is devoted to the development of such methodologies, then applied in the “Pays de Fougères”, a 1000 km² wide rural area located in the north-eastern Brittany in France. Firstly, a bio-resource mapping is drawn by applying a calculation method specific for each substrate. A derived layer, the energy potential grid (EPG), is calculated as the sum of the energy potential at any point in the area (100 m resolution per pixel) considering for each substrate a maximum distance proportional to the energetic potential of the substrate. Next, sensitive areas (wetlands, distances from housing…) are identified as areas where the development of biogas plants is restricted, resulting in a constraint map (CM). A final suitability map is constructed by combining the CM and the EPG, synthesized in the form of a raster GIS file. To go further on this issue, the network analysis capability of GIS is used, in order to take into account the actual transport route and competitive access to bio-resources. As a result, it allows refining the diagnosis of candidate sites. This study initiates the construction of a GIS model to determine optimal sites for collective biogas plants. The specificity of the approach is that methodologies are implemented to reach a very fine level of spatialization. The precise geolocation of farms is successfully obtained through the analysis of aerial photographs and Landsat imagery is used to help the identification of crop residues. However, some improvements could be implemented in the future, such as assigning a weight factor to the bio-resources reflecting their relative importance (liquid/solid form, no additional N content in the digestate, etc.). Although this mapping provides a basis for discussion in the context of decision support, it does not allow itself to make a choice on a future location, particularly since in the investigated area, the availability of bio-resources is not a major barrier (range from 6800 to 9300 ton of oil equivalent (toe)/year). Complementary parameters could be considered like social acceptance and environmental concerns generated by such a collective biogas plant. To explore this aspect in depth, the question of local impacts like eutrophication should be taken into consideration. Thus, beyond this GIS-based model, in order to test different scenarios for the development of collective biogas plants, a Life Cycle Assessment (LCA) is realised, assessing the environmental impacts of three scenarios as described in the paper of Aissani (2012). Future work will be to link more closely the GIS in LCA studies through the integration of spatial data and the spatial differentiation of local environmental impacts, the ultimate goal being to build a generic model for maximizing energy recovery from bio-resources in conjunction with a low environmental impact.

1 INTRODUCTION

1.1 Background

Agriculture substantially contributes to anthropogenic emissions of both N_2O and CH_4 as well as ammonia (NH_3). As signatories to international conventions, EU Member States are obliged to reduce their emissions. Moreover, the European Council (December 12, 2008) defined the energy-climate package and implemented a target called "3 X 20". The aim of this target is to reduce GHG emissions by 20% by 2020 compared to 1990 levels. It also aims to bring to a 20% share of renewable energy in the final consumption and to increase energetic efficiency by 20%. In response to these commitments, anaerobic digestion of livestock wastes is expected to expand in France in the coming years. The objectives of economic performance lead to a particular interest in centralized treatment plants involving other wastes, specifically wastes with high potential for energy production (agri-food waste, crop residues, etc.) which may be collected over long distances. However, such development is complex and requires the awareness of social and technical constraints (heat recovery, access to bio-resources...) as well as adhering to legal restrictions in the concerned areas.

1.2 Research objectives

In this context of potential development of collective biogas plants in France, the use of Geographic Information Systems (GIS) in order to georeference the bio-resources and then to locate the optimal sites appears very interesting and useful tools. Such investigations have been carried out on both national and regional scales (Batzias, 2005; Dagnall, 2010) but need to be adapted for local diagnosis. For this purpose, a research project is devoted to the development of such methodologies, and then applied in the “Pays de Fougères”, a 1000 km² wide rural area located in the north-eastern Brittany in France.

2 METHODOLOGY

The overall approach is summarized in the flow diagram (Figure 1) and requires GIS tools like Arcgis 10 Software. Extensions for Arcgis 10 such as Spatial Analyst and Network Analyst are used as well as Model Builder for automation issues. As an alternative, the main advanced functionalities are also successfully tested into the open source and free Software: GRASS. Firstly, a bio-resource mapping is drawn by applying a calculation method specific for each substrate. A derived layer, the energy potential grid (EPG), is calculated as the sum of the energy potential at any point in the area (100 m resolution per pixel) for each substrate considering a maximum distance proportional to the energetic potential of the substrate. Next, sensitive areas (wetlands, distances from housing…) are identified as areas where the development of biogas plants is restricted. Thus, buffer zones are used to set minimum distances away from sensitive sites, resulting in a constraint map (CM). A final suitability map is constructed by combining the CM and the EPG.

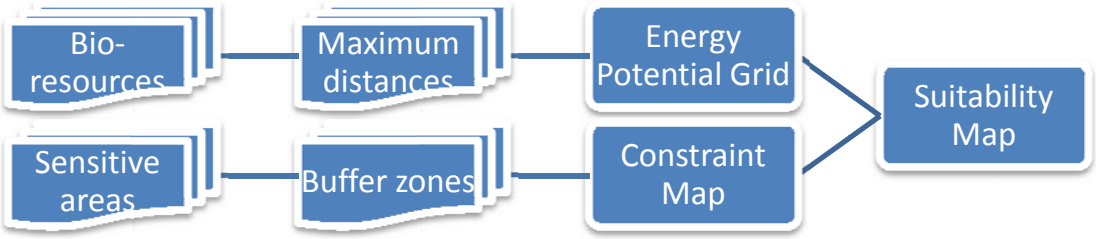

FIGURE 1: Flow diagram describing the successive steps of the geographical tree algorithm

2.1 Identification of the bio-resources

The identification of available bio-resources in a territory is the first step of diagnosis. Additionally, in order to take into account simultaneously all bio-resources, a similar unit has to be used. For that, each substrate is considered as regards to its potential recoverable energy. Such approach was developed by Tretyakov (2008) and is adapted, in this work, for a smaller territory (<1000 km ²). As a result, the relevant bio-resources and the methods to convert into energy potential are described in the following sections.

2.1.1 Manure

Annual census data from national statistical services of agriculture (SCEES) of the French Ministry of Agriculture providing information on the herd is used. These data are available at the NUTS 4 level (Nomenclature of Units for Territorial Statistics, Eurostat; 4 indicates a district level). To precisely map more the biogas potential of pig slurry and cattle manure, aerial photographs (50 cm pixel size) is used. A first step is the identification of the livestock buildings. Cattle buildings are identified as open buildings with natural light and ventilation and as buildings located near maize silage piles, while pig buildings are identified as closed building with forced ventilation, connected to a vertical grain silo and often linked to an external slurry tank. After such identification step, the digitization of livestock building areas is performed with the help of GIS edition tools. Finally, animal heads is calculated for the considered livestock building area proportionally to the total livestock building areas of the district. Then, method of conversion into energy potential (in toe per year) is described below:

$$P_{m,i} = \sum_{n=1}^{\infty} \left(d_i . a_n . e_i . t_i . Bo_{m,i} . MCF \right)$$

Where:

$P_{m,i}$: Energy potential calculated for manure *m* of animal type *i* (in toe/year)

n: Particular livestock building, digitized with aerial photo-interpretation

d_i: Density (number of animals per m² of livestock building) for animal type *i* (e.g. cattle, swine), d_i remains homogeneous within a district (NUTS 4 level) and estimated as:

$$d_i = \frac{H_i}{S_i}$$

Where:

H_i: Heads counted at scale of the district (SCEES data)for animal type i

S_i: Sum of the areas (m^2) of the livestock buildings digitized for animal type i for the whole district

a_n: Area of a livestock building *n*

e_i: Annual animal excretion rate (kg of dry matter) for animal type *i*

t_i: Annual time spent indoors for animal type *i*, (corresponding to the percentage of recoverable manure)

$Bo_{m,i}$: Maximum methane producing capacity (m^3/kg of dry matter) for manure m of animal type *i*

MCF: methane conversion factors (m^3 of CH_4 to toe) = 10/11628

Where:

10: conversion of m^3 CH_4 to kWh

11628: conversion of kWh to toe

Note: In the following formulas, MCF and Bo remain the same. Later in this paper, these factors are not described again.

2.1.2 Crop residues

The European Council regulation (CE N° 1593/2000) established the requirement, in all Member States, to locate and identify agricultural parcels. To meet this requirement, France has set up the "Registre Parcellaire Graphique" (RPG) that is an online geographic information system including aerial orthoimagery with a homogeneous standard guaranteeing accuracy equivalent to cartography at a scale of 1:5000. Each year, farmers have to digitize their agricultural parcels and have to identify their crops. Then, data are downloadable, free of charge for users from http://www.data.gouv.fr/, in the GIS "Shp" format. Unfortunately, some information is not relevant for the purposes of a residue inventory. For instance, a similar indication "maize crop" is given either for maize silage or maize grain while both are very different as regards to residues. Indeed, the maize grain represents a very interesting biogas potential because the major part of the plant is currently left on the field, as a residue, while the whole plant is harvested for maize silage. For a local diagnosis, it is therefore necessary to discriminate these two agricultural practices by an identification using remote sensing techniques (analysis of chronicles of Landsat imagery). This technique allows to overcome the lack of information from RPG. A specific calendar of planting and harvesting is used and based on agricultural statistics, valid for the climatic zone of the studied area.

For instance, in France, as a supplement to RPG data, using a Landsat image from the first week of October allows the distinction between maize silage (harvested) and maize grain (not yet harvested). Method of conversion into energy potential is described by the formula:

$$P_j = s_j . y_j . r_j . re_j . Bo_j . MCF$$

Where:
P_j: Energy potential of the residues for the crop *j* (in toe/year)
s_j: Surface of the crop *j* in the studied area
y_j: Average total yield (kg of dry matter) of the crop *j* in the studied area
r_j: Total residue rate (kg of dry matter) for the crop *j*,
re_j: Effective residue rate (% of r_j). In some literature, two residue rates are detailed: a maximum residue levels coupled with an effective rate of residues, considering that the full potential cannot be mobilized for technical and practical constraints. Here, we consider these two notions simultaneously.

2.1.3 Wastes from Agro-food industries

Data regarding the type and the quantity of these substrates is collected through a survey and specific analyses of the wastes if necessary. Energy potential (in toe/year) is evaluated as:

$$P_k = n_k . Bo_w . MCF$$

Where:
P_k: Energy potential of waste for the industry *k* (in toe/year)
n_k: Waste quantity (kg of dry matter) for the industry *k*

2.1.4 Sewage sludge from wastewater treatment plants

In the French context, data can be localized precisely through information provided from the Ministry of Environment on website (http://assainissement.developpement-durable.gouv.fr/). The data is available with georeferenced coordinates and annual quantities. Formula to convert waste quantities into energy potential is similar to previous section.

2.1.5 Garden wastes from drop-off centers

As for wastes from agro-industries, data is collected through a survey and the conversion to energy potential is similar.

2.1.6 Food wastes from school canteens and hospitals

Information can be precisely georeferenced from a list of the establishments end their addresses delivered by the municipal service. Then, further investigations (phone survey, questionnaire) provide the number of residents allowing the calculation of the number of annual meals. The computation of energy potential is given by:

$$P_l = n_l . r . Bo . MCF$$

Where:
P_l: Energy potential of food wastes for the establishment *l* (in toe/year)
n_l: Number of annual meals for the establishment *l*

$$n_l = o . N_l$$

Where:
o: Number of meals per year and person for the type of establishment (e.g. school canteens or hospitals)
N_l: Number of persons in the establishment *l*

r: Remains of meals (kg of dry matter per meal)

2.2 Construction of the Energy Potential Grid

A necessary preliminary step to the construction of the energy potential grid is to define the maximum distance to collect the bio-resources. An approach is to consider such distance variable depending on the individual potential energy, some bio-resources having a higher methane producing capacity. In this paper, it is assumed that energy spent for transportation does not have to exceed a certain percentage (fixed to 2% in this study) of the energy potential of each considered substrate. The equation below, illustrates this assumption.

Where:

: Maximum allowed distance (km) to collect the bio-resource type *b* (e.g. cattle manure, food waste, etc.)

: Dry matter content *(%)* for the bio-resource type *b*

: Fuel consumption for the transport of a certain quantity of bio-resource with the use of a truck (in toe/kg.km), empty return included.

The use of georeferenced data and their computation in raster (i.e. matrix or grid) allow to spatialize the energy potential recoverable from bio-resources. A neighborhood GIS functionality named "Point Statistics" in Arcgis 10 Software requiring Spatial Analyst extension allows the calculation of statistics. Thus, it enables the sum of EPG on point features that fall in the neighborhood (within a user defined radius: $Dmax_b$) around each output raster cell (Figure 2, left part).

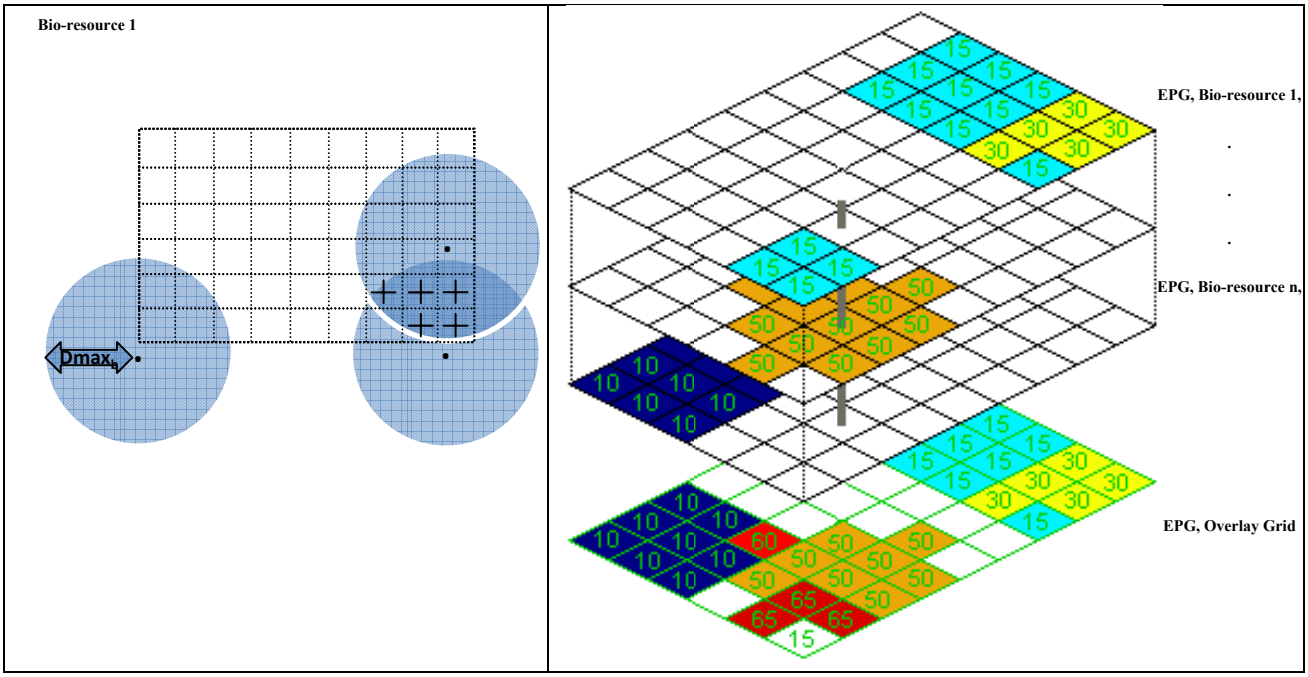

FIGURE 2: Neighborhood function (left part), raster output and EPG overlay grid obtained (right part)

The output is a new raster, with a user defined cell size. In the present study, 100 m resolution per pixel is chosen to achieve a good compromise between computation time and spatial accuracy. As an option, a weight factor can be set to reflect a percentage of defection, i.e. the more or less propensity to subcontract the management of each bio-resource. It is assumed to vary and be inversely proportional from 100% to 50% from point source to the maximum distance $Dmax_b$. Linear interpolation is set between these two extremes as described in the following formula:

Where:

: Weight factor of energy potential varying from 1 to 0.5 for bio-resource *b* at pixel position *p*

: Maximum allowed distance (km) to collect the bio-resource *b* (e.g. cattle manure, food waste, etc.)

: Distance (km) from bio-resource *b* to pixel position *p*

After applying such successive computation steps, an energy potential grid (EPG) is computable for each bio-resource. Then, the overlay grid of all the individual EPG provides the total potentially recoverable energy at any cell of the raster for the studied area (Figure 2, right part). An equivalence of such successive functionalities was successfully tested in the free Software GRASS ("r.neighbors" function). Red cells in the resulting grid represent the better locations in terms of potential energy.

2.3 Constraint Map

The spatial potential energy does not provide a direct mapping of candidate sites for collective biogas plants because exclusion zones must be considered, that is, areas where it is impossible to build due to regulatory requirements. Indeed, the French decree of 10 November 2009 establishes the technical commitments to be met by biogas plants. Within this framework, to summarize the regulatory constraints to apply, it is forbidden to install a biogas plant within (i) 50 m away from home, (ii) 35 m away from the perimeter of drinking water, and (iii) 35 m away from streams. In addition, protected areas in respect to (i) international commitments ("Biosphere Reserves" under the UNESCO program on Man and the Biosphere, "Ramsar sites" in application to the International Convention on Wetlands), (ii) European directives ("Natura 2000" sites based on the 1979 Birds Directive and the 1992 Habitats Directive), or (iii) national regulations (Regional Natural parks, classified sites, sensitive natural areas, etc.) must be inventoried and excluded from the area of interest. The European website http://ec.europa.eu/environment/nature/index_en.htm provides web links to download country specific georeferenced data. For instance, French environmental GIS data are accessible through web-services on http://inpn.mnhn.fr. Once these additional data are obtained, the creation of buffer zones and the conversion into raster make it possible to compute a constraint map (CM). A final suitability map is constructible by combining the CM and the EPG, as described by flow diagram of Figure 1. The use of automation tools like Model Builder in Arcgis 10 or like writing ".sh" files into GRASS is useful to chain the various functions and thus avoid rewriting each stage of calculations when a small adjustment to the geographical tree algorithm is required.

3 RESULTS AND DISCUSSION

A research project is devoted to the application of such spatial methodologies on a local scale in the "Pays de Fougères", a rural area of 1000 km², 82 000 inhabitants, located in the northeast of Brittany in France. The total potential energy for the whole area of interest is (high to low): 24 802, 10 369, 1 395, 268, 141 and 62 toe respectively for livestock manure, crop residues, wastes from Agro-food industries, garden waste from drop-off centers, sewage sludge from wastewater treatment plants and food wastes from school canteens and hospitals, totalizing 37 037 toe. Bio-resources from agriculture (e.g. manure & crop residues) stand for 95% of the total energy potential. This value should be tempered by the fact that agricultural substrates are scattered over the territory while other substrates can locally account for a high potential energy. Assuming an average consumption of 3.97 toe/capita.year (International Energy Agency, Key World Energy Statistics 2011), it would be possible to substitute 11% of the total energy consumed from residents, supposing that the entire potential energy is recovered. This proportion may appear low, but it could represent a significant interest in order to contribute in achieving the renewable energy commitments in France.

The specificity of the approach is that methodologies are implemented to reach a very fine level of spatialization for the evaluation of the energy potential. The precise geolocation of farms is successfully obtained through the analysis of aerial photographs. However, this identification technique is restricted to a limited area of application (< 1000 km ²) due to the time required for its implementation. For the example of crop residues, the Figure 3 illustrates the spatial differentiation observed between a global approach (a global rate of 30% of grain maize/silage maize is available at NUTS 3 level) and a more complex methodology, valid at the scale of agricultural parcels, using field declarative data (RPG) in combination with Landsat imagery analysis. The Figure 3 presents the aggregation of results at NUTS 5 level, for comparative purposes. While the global energy potential remains quite the same when comparing these two methods (about 10 000 toe), a different spatial distribution is noticed especially in the southeast of the area. Such observation emphasizes the fact that local diagnosis requires a precise methodology regarding bio-resource identification.

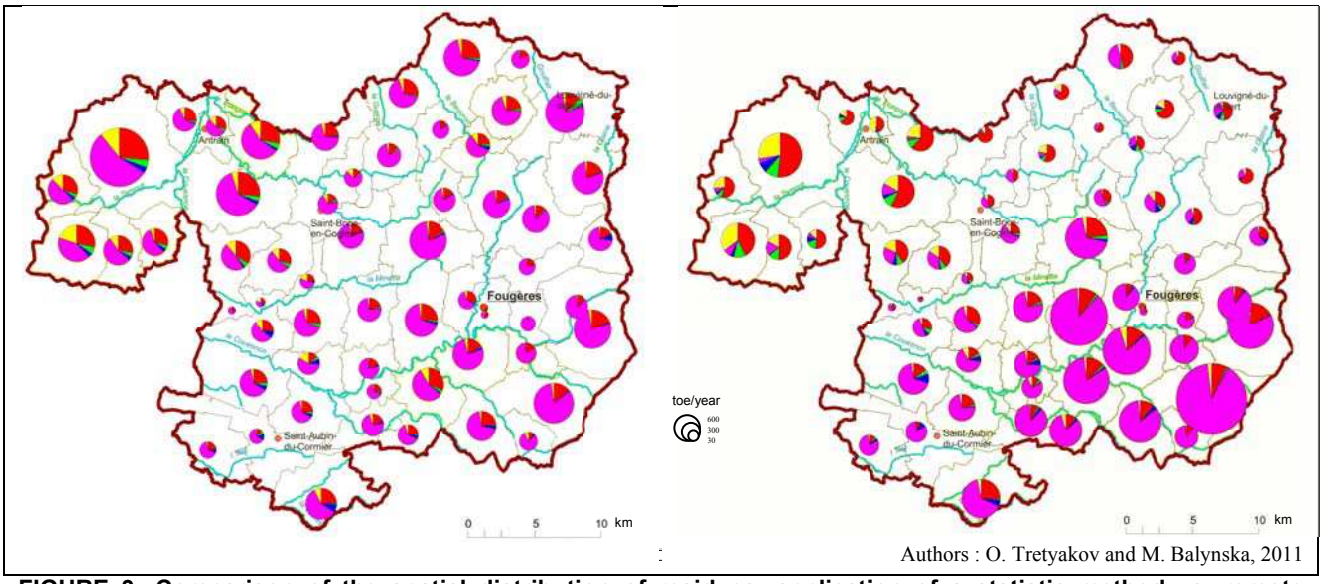

FIGURE 3: Comparison of the spatial distribution of residues, application of a statistic method vs. remote sensing analysis; red=winter wheat, pink=maize, green=barley, yellow=colza, blue=other cereals

The application of the methods described in § 2 (Energy Potential Grid in combination with a Constraint Map), leads to the construction of a suitability map (Figure 4) and identification of the most favourable areas. A percentage of defection is set varying from 100 to 50% from point source to the maximum distance $Dmax_b$. A gradient from blue to red reflects a rising value of the potential energy within the boundary established in terms of maximum distance allowed for each bio-resource. Such potential energy can reach over 9000 toe in the most candidate sites. To go further on this issue, as suggested in the paper of Ma et al. (2005), the network analysis capability of GIS (Network Analyst) is used, in order to take into account the actual transport route and competitive access to bio-resources. As a result, it allows refining the diagnosis of candidate sites. The benefit of such an option is to allow a better estimate of distances for the collection of substrates, leading to a lower (see the value in the tooltip of Figure 4) but a more accurate assessment of the potential energy at specific points in the territory.

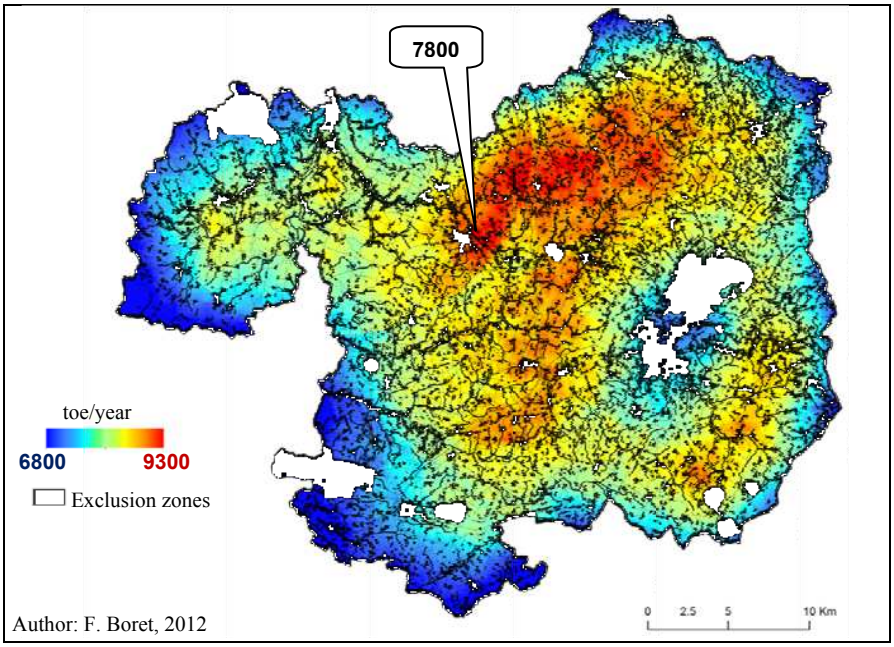

FIGURE 4: Suitability map obtained by combining the Constraint Map and the Energy Potential Grid

4 CONCLUSIONS

A significant proportion of bio-resources of the studied area could substitute for fossil fuel by recovering energy from local biomass. This study initiates the construction of a GIS model to determine optimal sites for collective biogas plants. This assessment is based on the computation of a potential energy from available bio-resources, synthesized in the form of a raster GIS file. To reach a very fine level of spatialization for the evaluation of the energy potential, a precise geolocation of farms is successfully obtained through the analysis of aerial photographs and Landsat imagery is used to help the identification of crop residues. Automation tools appear well-adapted to chain the various functions of the geographical tree algorithm. However, some improvements could be implemented in the future, such as assigning a weight factor to the bio-resources reflecting their relative interests (liquid/solid form, no additional N content in the digestate, etc.). A further question would be to consider other factors in the GIS model: (1) the gas pipelines network, which offers the option of introducing cleaned biogas into the pipeline instead of generating heat and electricity or (2) a deeper analysis of local heat energy needs. Although this mapping provides a basis for discussion in the context of decision support, it does not allow itself to make a choice on a future location, particularly since in the investigated area, the availability of bio-resources is not a major barrier (range from 6800 to 9300 toe/year). Complementary parameters could be considered like social acceptance and environmental concerns generated by such a collective biogas plant. To explore this aspect in depth, the question of local impacts like eutrophication should be taken into consideration. Thus, beyond this GIS-based model, in order to test different scenarios for the development of collective biogas plants, a Life Cycle Assessment (LCA) is realised, as described in the paper of Aissani et al. (2012), in order to assess the environmental impacts of three scenarios. Future work will be to link more closely the GIS with LCA studies through the spatial data integration and the spatialization of local environmental impacts, the ultimate goal being to build a generic model for maximizing energy recovery from bio-resources in conjunction with a low environmental impact.

5 ACKNOWLEDGEMENTS

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