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A spatially explicit model to analyse the regional supply of ligno-cellulosic biomass

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A spatially explicit model to analyse the regional supply of ligno-cellulosic biomass *

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1 Introduction

Throughout the world, the mitigation of greenhouse gas emissions is underway and the means to attain energy independence are under discussion. To this end, renewable sources of energy are being presented as alternatives to the finite supply of environmentally-problematic fossil fuels. To ensure progress in this direction, the European Union set mandatory targets in terms of the amount of energy produced from renewable sources. By 2020, that amount is to be 20% of the overall European Community's energy consumption and 10% of each Member State's energy consumption in the transportation sector alone (Parliament and the EU Council, DIRECTIVE2009-28-EC). Moreover, the European Commission laid stress on the importance of producing renewable energy sources on the local level so as to better secure the supply as well as to develop employment and rural opportunities. The commission also indicated that any production of an alternative source of energy needed to comply with economic, environmental, and social sustainability criteria [1]. According to Directive 2001/77/EC, "renewable energy sources" are defined as renewable non-fossil energy sources, ranging from wind, solar, geothermal, and hydropower to landfill gas, sewage treatment plant gas, biogases and biomass. The

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[1]Environmental sustainability criteria imply, for instance, a decrease by at least 35% (60% from 2018 on) of GHG emissions compared to the fossil fuels to which they substitute, including GHG emissions due to direct and indirect land use change. Renewable energy sources production must not occur at the expense of high biodiversity value land, primary forest, natural grasslands, and good quality agricultural land.

Directive further defines "biomass" as the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste.

For numerous reasons, biomass is expected to play an important role in reaching EU targets. First and foremost, it is renewable. Secondly, it can be cultivated in all regions. It can also be converted into heat, electricity or biofuels as well as stored in huge quantities.

First generation biofuels, from oil and starch crops, have been heavily subsidized to compensate for a lack of competitivity compared to fossil fuels and to support their development. However, doubt soon shadowed the worthiness of such incentives given the externalities of the production of these biofuels (Scarlat and Dallemand, 2011; Searchinger et al., 2008; Zilberman et al., 2013). Competition with food crops results in indirect land-use change, questionable environmental benefits, and even a negative carbon balance. First generation biofuels were also accused of being responsible for the food price crisis. Lastly, first generation biofuels were found not to comply with sustainability criteria.

Now, the focus has shifted to lignocellulosic bioenergy, including second generation biofuels. In this case, bioenergy is produced by processing the whole plant, in particular its lignocellulose (the main component of plant cell walls). There exists a wide range of lignocellulosic feedstocks including crop residues (such as cereal straw and corn stover), dedicated annual crops (such as fiber sorghum and whole plant triticale), dedicated perennial crops (such as Miscanthus and Switchgrass), woody biomass produced on agricultural land (such as poplar or willow short rotation coppices), and forest biomass (such as roundwood and remnants). In addition, lignocellulosic bioenergy chains are expected to be more compatible with sustainability criteria. First of all, lignocellulosic biomass usually has higher energy content and yields than food crops for lower input levels. Secondly, it can be grown on marginal land. Thirdly, it is possible to use crop residues and forest biomass, including trunks and remnants (branchwood usually left on the ground after logging). A major question remains: while complying with sustainability criteria, to what extent can the agricultural and the forest sectors contribute to the production of lignocellulosic bioenergy at both global and regional scales?

This question has been tackled using various approaches in several studies (see Berndes et al., 2003, for a review of 17 studies at the global level; EEA, 2006; Ericsson and Nilsson, 2006; and Fischer et al., 2010 for an assessment of the overall EU biomass potential production). These studies showed that a large-scale biomass supply is technically feasible and that EU policy targets are technically achievable, even without harming the environment. They all conclude that agricultural and forest residues represent large, unexploited, biomass resources, but that dedicated energy crops and short rotation coppices on agricultural land have the largest biomass potential in the medium-long term. However, this potential is contingent upon assumptions regarding surplus agricultural land available to grow energy crops and the yields themselves. These studies therefore highlight the importance of accounting for land-use competition between food and bioenergy production as well as for farming practices and the pedoclimatic context influencing yields. They also indicate the need to complement these large scale assessments with more regional and local-scale studies.

The agropedoclimatic context will be key in determining if and where a given crop species can be grown, together with the appropriate cropping technique and the corresponding yield, production cost, and environmental impacts. As many crop species can be grown at a given place (resulting in land-use competition), it is their relative profitability (income minus production cost) that determines land-use allocation. Very often researchers make strong assumptions on land availability, such as excluding from energy feedstock cultivation the areas necessary to fulfil future requirements in terms of food, feed, and nature preservation ("food, feed, and nature first" paradigm). This is for instance the case in Fischer et al. (2010) and de Wit and Faaij (2010) (REFUEL project) studies, in which biomass supply curves were generated for EU27 based on detailed agropedoclimatic potential, accounting only for production costs. van der Hilst et al. (2010), Ugarte and Ray (2000), and Ballarin et al. (2011) compared net present values of lignocellulosic crops and food crop rotations to allocate land on a limited share of the agricultural area, given exogeneous biomass prices. However, there is no existing market for lignocellulosic crops, which are new commodities. Their price will be determined locally, as transportation costs are expected to be high with respect to the biomass value (due to its low density). Farmers are likely to grow them only if a local bioenergy chain emerges and if the price they are offered covers at least their opportunity cost. The latter depends on the foregone revenues from the best alternative, the production cost, and the delivery cost (to a conversion plant). If foregone revenues due to land-use substitution and competition are not accounted for, then part of the biomass opportunity cost goes unaccounted for, leading to its underestimation. The above-mentioned studies therefore most likely misestimate biomass supply costs. If, instead, land use competition is more accurately taken into account, we should be able to better estimate the type and quantity of biomass that can be supplied as well as the associated opportunity cost, providing thereby a more detailed picture of what can happen at the local level.

The relative location of feedstock and bioenergy facilities has an impact on the supply cost of the facility, but also on the choice of the type of biomass delivered to the plant, for low transport costs can compensate for a difference in farm gate/on-site cost between two types of biomass. Many studies addressed the issue of the optimum siting and/or sizing of conversion plants, in relationship to their competitiveness. But they often account for (fixed) exogeneous biomass quantities and costs (Leduc et al., 2009; Tittmann et al., 2010; Lensink and Londo, 2010; Londo et al., 2010). Schmidt et al. (2010) optimized the whole supply chain but only considered forest biomass.

Finally, it is important to have a detailed modelling of the supply side to better account for the actual lignocellulosic biomass supply and its impact on land-use change. Production, land-use, and resource allocation decisions are taken locally by private landowners or managers (i.e., farmers or forest managers), that basically maximize their gross margin, subjected to technical and policy constraints and accounting for the price context. Microeconomic, farm-based, agricultural supply models are widely used to assess the impacts of agri-environmental and energy policies, in the field of agricultural economics. They have been used to assess the competitiveness and impacts of the first generation biofuels (Rozakis and Sourie, 2005; Sourie et al., 2005; Guindé et al., 2008). For instance, Rozakis and Sourie (2005) showed that tax exemptions for first generation biofuels in France were overestimated and could be decreased by 10-20% with no risk for the viability of these chains. However, these models are generally not spatially explicit and do not account for the location of conversion plants, nor for transportation issues. If they do try to locate biomass production, it is generally by means of downscaling or probability maps.

To accurately address the issue of the sustainability of agricultural and forest lignocellulosic bioenergy chains (in terms of competitiveness and environmental impacts), it is important to account, at a local level, for land-use competition and substitution, spatial distribution of bioenergy crops and biomass production, and logistics constraints (Hellmann and Verburg, 2011; Petersen, 2008). The location of conversion plants with regard to feedstock availability is a specific issue: it plays a role in both competitiveness - through transportation costs - and environmental impacts -through fuel consumption for instance.

To our knowledge, no study has accounted for all these factors. In this paper, we set out to do so. We model biomass supply at a local scale accounting for agricultural and forest biomass in a detailed manner, land-use competition, transportation costs, and the optimal location of bioenergy facilities. At the same time we account for the competition between agricultural and forest biomass for energy uses. Within an overall project to assess the competitiveness and environmental impacts of the production of bioenergy from lignocellulosic biomass, we examine plant location, land allocation, biomass supply costs, and environmental impacts in relation to the demand for cellulosic feedstock at the regional (Nuts 2) level. More precisely, we address the following questions: i) what type and quantity of biomass can be supplied at the regional level and for what price depending on the economic context; ii) where will the biomass source be cultivated and where will the conversion plants be located in relationship to supply location; and iii) what is the impact of plant location on both the choice of biomass to be grown and the supply cost?

To tackle these questions, we have developed a spatially-explicit regional supply model with a county sub-level for agricultural and forest lignocellulosic biomass. The model maximizes the agricultural and forest gross margins of the region, taking into account all of the following: transportation distances and costs from counties to bioenergy facilities, the (facilities) demand for biomass in primary energy equivalent, soil characteristics, biomass and crop yields and production costs as well as available wood quantities per category, the related stumpage and harvesting costs, and the various potential uses of biomass (food, energy, industry or timber). The model endogenously determines the optimal location of facilities within a region in addition to agricultural land allocation in counties as well as types and quantities of wood supplied.

As an illustration, we have applied this modelling approach to the case of the French Champagne-Ardenne region. It has enabled us to generate the first lignocellulosic biomass supply curves for France, to perform a sensitivity analysis to the food crops price context, and to bring under scrutiny well-accepted claims concerning the production and supply of lignocellulosic biomass in France. It is widely thought that: Miscanthus is the dedicated energy crop to be grown in France; that forest remnants will be massively used for energy purpose; and that perennial dedicated crops will be grown on marginal land thus lower the competition with food crops for land. How do these claims hold up when confronted with our results for the given region?

The article is structured as follows. The methodological aspects involving the modelling approach are covered in Section 2. In Section 3, the case study and the applied model are described, and the simulation scenarios and hypotheses are introduced. In Section 4 we discuss the results. In Section 5, we sum up the overall advantages of our spatially-explicit approach and bring under discussion the three above-mentioned claims about the production and supply of lignocellulosic biomass in France. In Section 6, perspectives, we make suggestions for further development and applications of the model.

2 Methodology

A spatially-explicit regional supply model for agricultural and forest lignocellulosic biomass has been developed, that accounts for two spatial levels : the county and the region. The model maximizes the agricultural and forest incomes of the region, taking into account the demand for lignocellulosic biomass, transportation distances and costs from counties to bioernergy facilities, food and energy crops yields and production costs in relation to soil characteristics, available wood quantities per category and the related stumpage and harvesting costs, and the various potential uses of biomass (food, energy, industry or timber). The model endogenously determines agricultural land allocation, harvested wood quantities per category, as well as the type, quantity, conditioning, and origin of lignocellulosic biomass supplied to bioenergy facilities. It also determines the optimal location of facilities within a region, if it is not initially given. The presented model accounts for two spatial levels: the county and the region. The county has been chosen as the elementary unit as it is an administrative (sub) level for which data are available, and it provides the framework for locating biomass departure and delivery points at the county seats. It is characterised by its agropedoclimatic context, its altitude, and the slope of forest stands. In this model it is the level at which production decisions occur, taking into account technical and economic constraints. I.e, the county iehaves as a farm or forest manager. The region is the relevant level when it comes to drawing the boundaries of the biomass supply area and studying the competition for resources arising when different bioenergy facilities are being set up at the same time or over time. It is the level at which transportation costs and logistics issues are accounted for.

We assume here that agricultural and forest areas are independent, i.e., deforestation and afforestation are not allowed, and that short rotation coppices (SRC) can only be grown on agricultural areas. A schematic overview of the model inputs and outputs is provided in Fig. 1. This model is a mixed integer programming model written in GAMS and solved with the CPLEX solver.

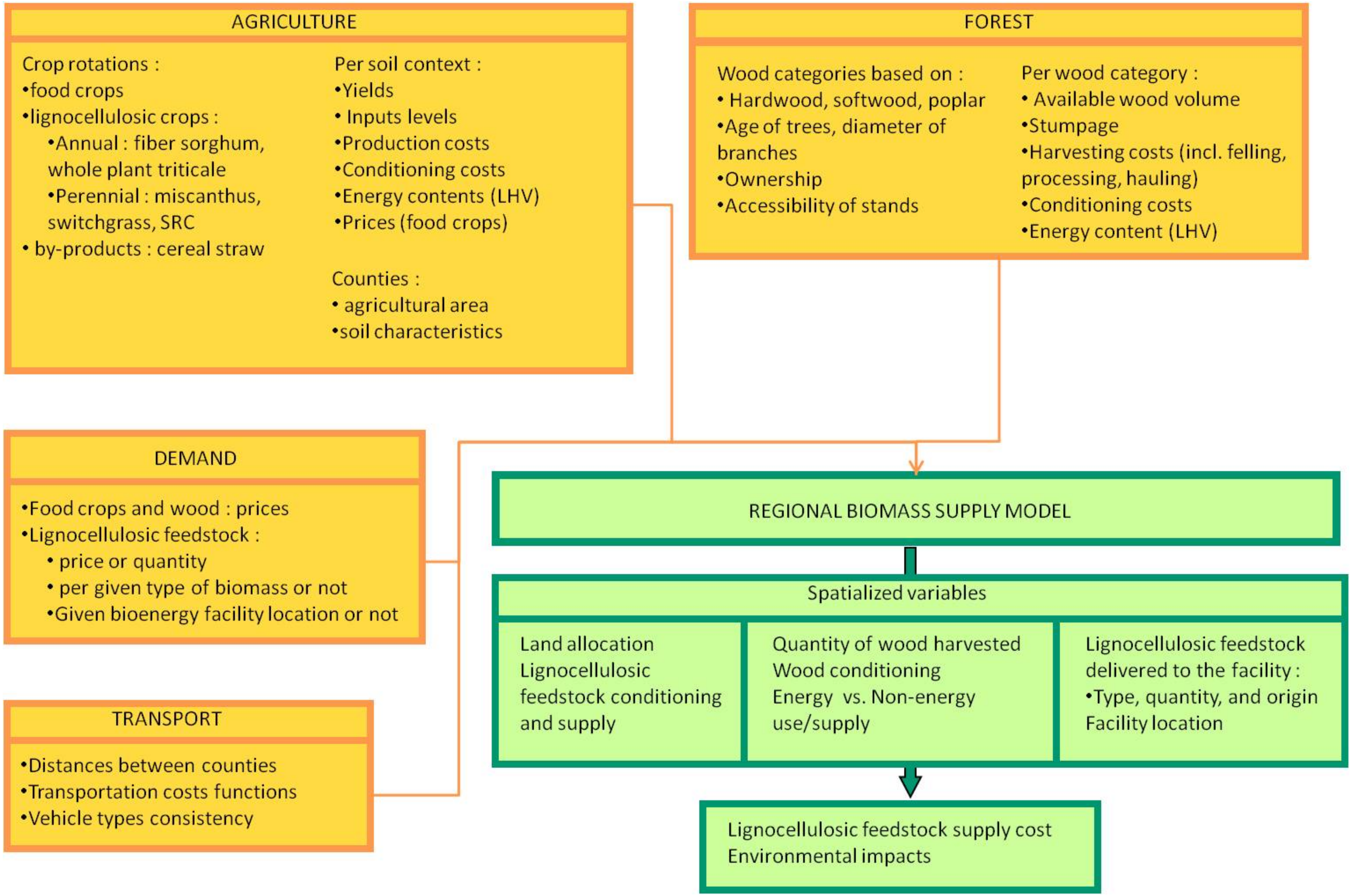


Fig. 1. Schematic overview of the model inputs and ouputs

2.1 Model description

We provide here a stylised version of the model and then further detail the activities and constraints in the following subsections.

2.1.1 Objective function

The model maximizes the region's gross margin, i.e., the sum of counties' gross margin for agricultural ($\Pi_i^{CROPS}\left(S_i^{ROT}\right)$) and forest ($\Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right)$)activities, including biomass production for bioenergy ($\Pi_i^{ENERGY}\left(X_i^{ENERGY}\right)$), minus transportation costs for the biomass delivered from production sites to bioenergy facilities ($T_{i,j}^{ENERGY}\left(LBD_{i,j}^{ENERGY}\right)$) (Equation (1)).

$$\max_{X_i, LBD_{i,j}, (locus_j)} \sum_i \left(\Pi_i^{CROPS}\left(S_i^{ROT}\right) + \Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) + \right. \\ \left. + \Pi_i^{ENERGY}\left(X_i^{ENERGY}\right) \right) - \sum_{i,j} T_{i,j}^{ENERGY}\left(LBD_{i,j}^{ENERGY}\right) \cdot locus_j \quad (1)$$

where i and j are respectively the indices for departure and arrival counties; $LBD_{i,j}^{ENERGY}$ is the amount of lignocellulosic biomass (energy crop, straw or wood) delivered to county j from county i (tons); $locus_j$ is equal to 1 if a bioenergy facility is located in county j and to 0 otherwise.

2.1.2 Constraints

Constraint 2 sets that the areas $S_{r,s,i}^{ROT}$ grown with rotations including food and/or energy crops must be less than the total agricultural area UAA_i in each county.

$$\sum_{r,s} S_{r,s,i}^{ROT} \leq UAA_i, \quad \forall i \quad (2)$$

Constraint 3 links crops production $X_{c,s,i}^{CROPS}$ to the area dedicated to the various crop rotations $S_{r,s,i}^{ROT}$, given the yield $y_{c,s}$ of crop c on soil s and its share $\gamma_{c,r}$ in rotation r.

$$X_{c,s,i}^{CROPS} = \sum_r \left(y_{c,s} \cdot \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right), \quad \forall c, s, i \quad (3)$$

Constraint 4 relates the amount of straw that can be used for energy purpose X_i^{EStraw} to the area grown with cereal crops, given $y_{c,i}^{straw}$ the yield of straw from cereal crops c in the county, and limits it to the share α_i that can be exported without harming the soil organic matter content.

$$X_i^{EStraw} \leq \sum_{r,s} \left(\alpha_i \cdot y_{c,i}^{straw} \cdot \gamma_{c,r} \cdot S_{r,s,i}^{ROT} \right), \quad \forall i \tag{4}$$

Constraints 5 and 6 limits the amount of wood that is harvested for energy (X_i^{EWood}) and non-energy (X_i^{NEWood}) uses to the amount available annually($\overline{W_i^{WOOD}}$), accounting for wood density (ρ).

$$W_i^{WOOD} \leq \overline{W_i^{WOOD}}, \quad \forall i \tag{5}$$

$$\rho \cdot \left(X_i^{NEWood} + X_i^{EWood} \right) \leq W_i^{WOOD}, \quad \forall i \tag{6}$$

The lignocellulosic feedstock supply in each county X_i^{ENERGY} equals the sum of its annual and perennial dedicated crops X_i^{ECrop}, cereal straw X_i^{EStraw}, and wood X_i^{EWood} supply (Equation (7)).

$$X_i^{ECrop} + X_i^{EWood} + X_i^{EStraw} = X_i^{ENERGY}, \quad \forall i \tag{7}$$

A county i cannot export more lignocellulosic feedstock to other counties j than its own production (8).

$$X_i^{ENERGY} \geq \sum_j LBD_{i,j}^{ENERGY}, \quad \forall i \tag{8}$$

The total amount of lignocellulosic biomass delivered to a county j must satisfy the facility's demand (D^{ENERGY}), if it exists (i.e. $locus_j = 1$), accounting for the feedstock energy content (lhv^{ENERGY}) (Equation (9)).

$$\sum_i LBD_{i,j}^{ENERGY} \cdot lhv^{ENERGY} = D^{ENERGY} \cdot locus_j, \quad \forall j \tag{9}$$

$locus_j$ is a binary variable equal to 1 if a bioenergy facility is located in county j and to 0 otherwise. All other variables must be equal to or greater than 0.

$$W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}, S_{r,s,i}^{ROT}, LBD_{i,j}^{ENERGY} \geq 0 \tag{10}$$

2.2 Agricultural biomass

In this model we have chosen to optimize the area of crop rotations, rather than the area of crops. Crop rotations better take into account the preceding and following crop effects on yields, input consumptions (nitrogen balance for instance) and environmental impacts. Moreover, it facilitates the comparison of crop rotations (composed of annual crops) to perennial crops such as miscanthus and short rotation coppice. We assume that farmers will substitute perennial crops for existing crop rotations and annual dedicated crops, such as whole plant triticale, for equivalent crops in crop rotations. Our crop rotations are based on existing ones or ones that could be used on each of the soil types. We also account for by-products such as cereal straw.

Equations 11 to 13 detail the components of food crops, dedicated energy crops, and straw gross margins, included in the objective function.

$$\Pi_i^{CROPS}\left(S_i^{ROT}\right) = \sum_{c,s}\left(\left(p_c \cdot y_{c,s} - c_{c,s}^{prod}\right) \cdot \sum_r \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right) \tag{11}$$

$$\Pi_i^{ENERGY}\left(X_i^{ECrop}\right) = \sum_c\left(\left(p^{MWh} \cdot lhv_c - c_c^{cond}\right) \cdot X_{c,i}^{ECrop}\right) \tag{12}$$

$$\Pi_i^{ENERGY}\left(X_i^{EStraw}\right) = \left(p^{MWh} \cdot lhv_{straw} - c_{straw}^{cond}\right) \cdot X_i^{EStraw} \tag{13}$$

2.3 Forest biomass

In this model, forest biomass is accounted for in terms of existing forests according to the following characteristics: area, location, ownership, species, age of trees (young or medium-sized trees and old or big-sized trees), and slope of the plots. Medium-sized trees have small and medium diameter branches, whereas big-sized trees have small, medium and big diameter branches. Knowing the age and composition of forest plots, we can assess the amount of wood of each diameter that is available. Depending on diameter, wood can be conditioned into logs, bundles or wood chips (see Fig.2). It is possible to cut trees, to condition and export only a part of the wood, and leave the rest on the ground (e.g. it is often the case of remnants).

Equations 14 to 15 detail the components of forest activities' gross margins, included in the objective function.

$$\Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) = \sum_{w,cond}\left(p^{wood} \cdot X_{w,cond,i}^{NEWood}\right) - \\ - \sum_{w,cond}\left(c_{w,cond}^{stump} \cdot W_{w,cond,i}^{WOOD} + c_{w,cond}^{harv} \cdot \left(X_{w,cond,i}^{NEWood} + X_{w,cond,i}^{EWood}\right)\right) \tag{14}$$

$$\Pi_i^{ENERGY}\left(X_i^{EWood}\right) = \sum_w p^{MWh} \cdot lhv_w \cdot X_{w,i}^{EWood} \tag{15}$$

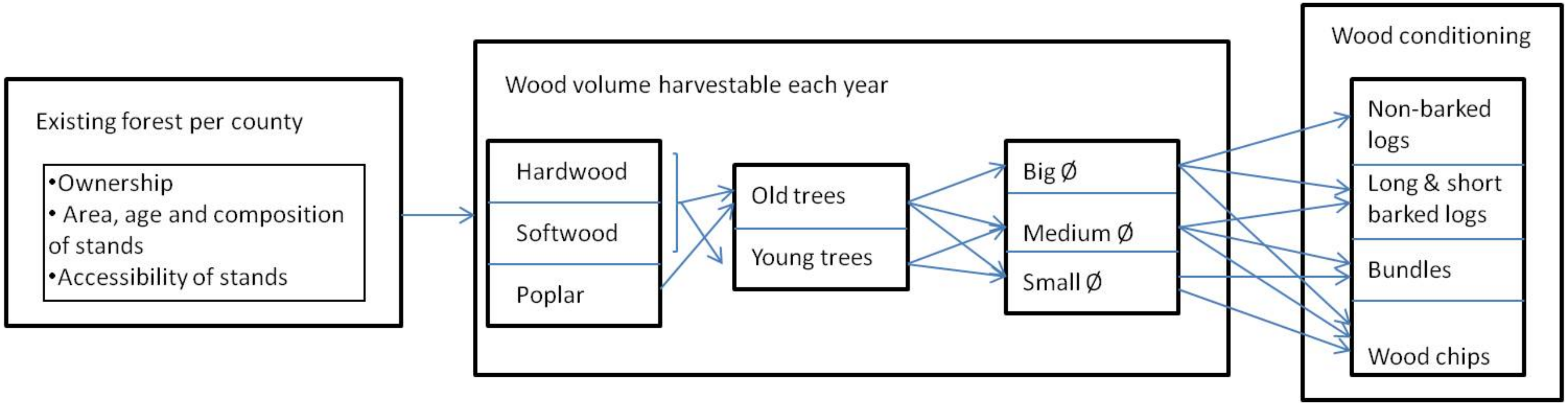


Fig. 2. Determination of the annually harvestable wood volume and its potential conditioning, depending on the existing forest characteristics

2.4 Demand

We assume here that farmers and forest managers are price-takers. The demand for food crops and non-energy wood is accounted for by means of the regional market prices. The demand for agricultural and/or forest lignocellulosic feedstock is expressed either in terms of i) quantity : i.e., in our case for a matter of simplicity, in primary energy content equivalent; or ii) price: i.e., in euro per unit of primary energy content. The demand can also be spatially located within the region, for instance when a bioenergy facility is to be supplied with lignocellulosic feedstock. For reasons of simplicity and computation time issues, we assume that a facility can only be located at the county seat. The location of the facility can be either fixed (i.e. *locus* becomes a parameter) or optimized by the model (i.e. *locus* is a decision variable).

2.5 Transportation

In this model, we consider simplified transportation costs per ton and per kilometre while minimizing total lignocellulosic feedstock supply cost, including delivery costs[2]. The cost ($t_{c,cond,vcl,i,j}$ or $t^{EWood}_{w,cond,vcl,i,j}$) of transporting a ton of lignocellulosic feedstock from county i to county j depends on : i) the distance $d_{i,j}$ between the two counties; ii) the type of conditionning (*cond*) of the biomass (e.g., silage, high density bales, logs, wood chips, etc.), which influences its density; iii) the type of vehicle (*vcl*) which is being used. We assume that all biomass is already available at the county seat. However, when the source of biomass and the facility are located within the same county, the transportation charge is a fixed one.

Agricultural biomass transportation costs per ton are accounted for in the form of a piecewise linear function of the distance, over distance class intervals (Equation (17)). We consider a fixed cost $\epsilon_{c,cond,vcl,cld}$ for intra-county delivery only (i.e., $i = j$ and $d_{i,j} = 0$), which is otherwise nil.

$$T^{ECrops}_{i,j}\left(LBD^{ECrops}_{c,i,j}\right) = \sum_{c,cond,vcl}\left(t_{c,cond,vcl,i,j} \cdot LBD^{ECrops}_{c,cond,vcl,i,j}\right) \tag{16}$$

with :

$$t^{ECrop}_{c,cond,vcl,i,j} = \delta_{c,cond,vcl,cld} \cdot d_{i,j} + \epsilon_{c,cond,vcl,cld} \tag{17}$$

[2]This is equivalent to maximizing the sum of counties' gross margin for agricultural activities, including biomass production for bioenergy, minus biomass delivery cost from production sites to a bioenergy facility

and cld being the distance class to which belong $d_{i,j}$; $\delta_{c,cond,vcl,cld}$ and $\epsilon_{c,cond,vcl,cld}$ being the parameters of the dedicated crop transportation cost function (in €/km and €, respectively).

Forest biomass transportation costs per ton are accounted for in the form of a quadratic function of the distance (Equation (19)).

$$T_{i,j}^{EWood}\left(LBD_{w,i,j}^{EWood}\right) = \sum_{w,cond,vcl}\left(t_{w,cond,vcl,i,j}^{EWood} \cdot LBD_{c,cond,vcl,i,j}^{EWood}\right) \quad (18)$$

with :

$$t_{w,cond,vcl,i,j}^{EWood} = \vartheta_{c,cond,vcl}^{EWood} \cdot d_{i,j}^2 + \delta_{c,cond,vcl}^{EWood} \cdot d_{i,j} + \epsilon_{w,cond,vcl}^{EWood} \quad (19)$$

and $\vartheta_{c,cond,vcl}^{EWood}$, $\delta_{c,cond,vcl}^{EWood}$, and $\epsilon_{w,cond,vcl}^{EWood}$ being the parameters of the quadratic transportation cost function for wood (in €/km^2, €/km, and € respectively).

3 Case study

The above-described spatially-explicit model and the associated generic methodology were initially developed within an interdisciplinary project, in collaboration with agricultural and forest technical institutes. To test the methodology, the French Champagne-Ardenne region was selected for numerous reasons. It is made up of 146 counties with both agricultural and forest activities and different types of lignocellulosic crops can be grown there [3]. Moreover, research and development activities focused on second generation biofuels are already being carried out in this region. We decided to only account for the utilised agricultural area (UAA) of cash crop farms (Types of Farming 13 and 14 in accordance with the FADN classification), as we do not model breeding and dairy farms. We do not account for permanent grassland areas in the model, as they are fixed over time, and therefore removed them from the cash crop farms UAA in each county in equation 2). Below, we first describe the tested scenarii and the hypotheses. Data sources for the test region are then detailed, and the validation of the model is presented.

3.1 Scenarii and hypotheses

First, we simulate individual biomass supply curves for switchgrass, miscanthus, whole plant triticale, fiber sorghum, poplar SRC, forest biomass, and wood chips (either from

[3]Detailed information on the agricultural and forest sector of the region can be found in a project deliverable (Bamière, L. et al., 2007)

poplar SRC or forest biomass). To do so, we introduce a price for the bioenergy feedstock under consideration in the objective function and we then simulate the quantity of this feedstock that is made available at the regional level.

Second, we simulate the potential total lignocellulosic biomass supply curve for the Champagne-Ardenne region, accounting for the competition between the various biomass feedstock sources. To do so, we introduce a price for lignocellulosic feedstock (in MWh equivalent) in the objective function and we then simulate the type and quantity of the various feedstock sources that are made available at the region level.

In both cases, locus is a parameter set to 0 and equations 8 and 9 are removed.

Finally we simulate the setting up of a second generation ethanol production facility. The facility is characterized by its use of enzymatic hydrolysis and fermentation to produce bioethanol from lignocellulosic biomass, with a target production of 180 million liters of ethanol per year. These characteristics correspond to a project under study in the region[4]. To do so, we introduce a demand for lignocellulosic biomass in equation 9, that forces the model to satisfy the facility's demand. We look for the best facility location, the type and quantity of biomass supplied as well as the corresponding supply costs. As we optimize the facility location, locus is considered as a variable.

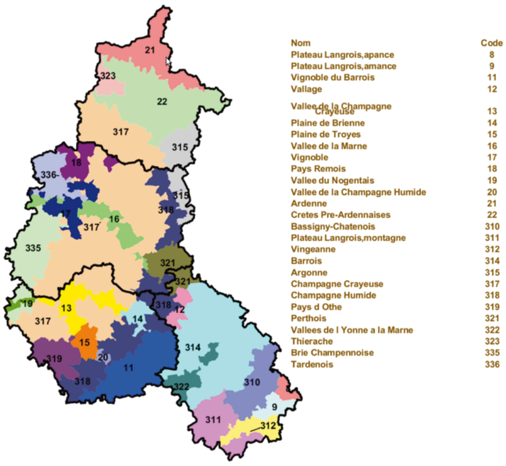
In each case, we perform a sensitivity analysis of our results to the agricultural prices context.

3.2 Soil and agricultural data

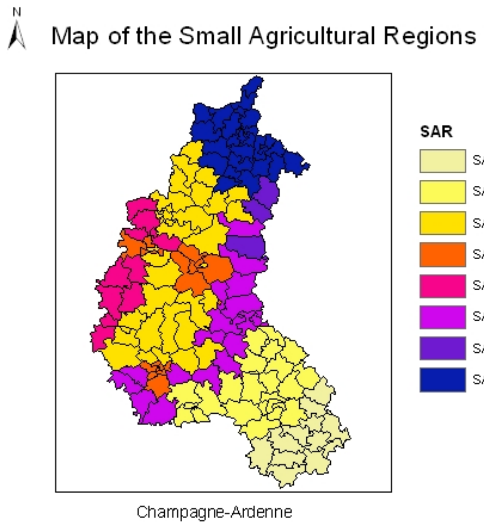
We have chosen to account for the agropedoclimatic context by the use of Small Agricultural Regions (SARs, INSEE classification). Small Agricultural Regions define homogeneous agricultural areas from the pedoclimatic and production context point of view. For a matter of simplicity, the 27 SARs of the Champagne-Ardennes region (Fig. 3a) were clustered into 8 homogeneous groups, hereafter mentioned as SAR1 to 8 (Fig. 3b). The maps of these 8 SARs and the counties were then overlaid to determine the dominant SAR in each county.

We first identified the food and energy crops that are or could be grown on each SAR, as well as the existing crop rotation patterns in the region. We then conceived the crop rotations to be included in the model, based on this information. In Champagne-Ardenne, cropping systems are very diversified with a large range of heads of crop rotations including rapeseed, beetroots, peas, and vegetables. A wide range of possible crop rotations therefore exists. However, in our case, the actual crop rotations adhere to three main

[4] Futurol-Procethol2G project : http://www.projet-futurol.com/index-uk.php



(a) Map of the 27 Small Agricultural Regions of the Champagne-Ardenne region.



(b) Map of the 8 groups of Small Agricultural Regions (SAR1 to SAR8) of the Champagne-Ardenne region.

Fig. 3

patterns. The eligible food crops were inserted into these patterns to obtain 23 food crop rotations (see tables 17 to 19 in appendix). Concerning annual dedicated crops, whole-plant triticale substitutes for barley in rotations, while fibre sorghum substitutes for maize. Miscanthus and switchgrass require 16-year rotations, including one year to ready the plot. They are harvested every year as of the third year until the fifteenth year. Given this procedure, we obtained 9 energy crop rotations (see Table 20 in appendix). As mentioned before, short rotation coppices are only grown on agricultural areas. Three types of poplar SRC were differentiated based on the suitable pedoclimatic context for their production, the cropping technique, and the associated yield level. Poplar SRC require 21-year rotations harvested every 7 years.

Finally, any available data on agricultural practices, crop yields and production costs were gathered for each SAR. Yield data culled from different regional sources were compared so as to compute average yields for conventional crops over a 10-year period for each SAR. Three types of wheat are differentiated based on the preceding crop, leading to different yield and production cost levels. Data from the same regional sources involving yields were used to compute average production costs (including seeds, fertilisers, herbicides, and pesticides) over the 10-year period for each food crop in each SAR. Yields and production costs for dedicated energy crops were estimated from field trial results. For poplar SRC and each perennial crop, an average annual yield and an equivalent annual cost are computed over the whole duration of the rotation (including the non-productive years, and with a 5% discount rate for the costs). Yield and production cost data for crops and SRC are gathered in Table 1, Table 2 and Table 3 respectively. For a matter of comparison and consistency, we use the equivalent annual costs of crop rotations and SRC in the model.

We perform the simulations for three agricultural price context scenarios (see Table 4). In the benchmark scenario, food crop prices correspond to the mean prices for 1993-2007. In the "low prices" and a "high prices" scenarios, they correspond respectively to the 1^{st} and the 9^{th}decile of 1993–2007 prices.

To assess the environmental impact of a demand for agricultural lignocellulosic biomass, in terms of pesticide and herbicide use, we use data on the average number of treatments for each crop per hectare, per year, and per SAR (c.f. Table 5). We compute : i)the average number of treatments per hectare for each county, each SAR, and for the region; ii) the total number of treatments for each county, each SAR, and for the region.

Moreover, most of the region is classified as "‘vulnerable zone"’ under the Nitrates Directive (Directive 91/676/EEC, see figure 18). As a consequence, agricultural areas are subjected to constraints on nitrogen fertilisation practices. Therefore, we also assess nitrogen fertilision level, using data on average fertilisation level for each crop per hectare, per year, and per SAR (c.f. Table 6). This information on nitrogen input levels cannot be used as a proxy to assess environmental impacts due to fertilisation. To do so, one should assess excess nitrogen considering crops needs and input use, which we do not.

Detailed information on soil and agricultural data sources and processing can be found in appendix (c.f. table 16).

	SAR1		SAR2		SAR3		SAR4	
	yield	production cost	yield	production cost	yield	production cost	yield	production cost
Wheat (after Wheat)	6.0	340.0	6.5	340.0	7.9	365.4	8.4	370.0
Wheat (standard)	6.4	330.0	7.0	330.0	8.5	355.4	9.0	360.0
Wheat (after good preceding crop)	6.7	315.0	7.4	315.0	8.9	340.4	9.5	345.0
Spring Barley	4.6	350.0	5.1	250.0	6.7	275.0	7.0	300.0
Winter Barley	6.2	0.0	6.7	345.0	8.0	340.0	8.5	350.0
Rapeseed	3.1	345.0	3.1	390.0	3.6	365.0	4.0	370.0
Sunflower	2.5	360.0	2.5	280.0	3.0	310.0	3.3	280.0
Maize	6.5	280.0	6.5	380.0	9.0	400.0	10.0	460.0
Spring Pea	3.9	380.0	4.0	270.0	4.3	280.0	5.5	270.0
Winter Pea	4.3	250.0	4.3	235.0	4.3	260.0	4.5	260.0
Horsebean Pea	4.3	0.0	4.3	285.0	4.3	285.0	4.5	285.0
Sugar Beet	0.0	0.0	0.0	0.0	90.0	700.0	90.0	700.0
Food Potatoe	0.0	0.0	0.0	0.0	48.5	2290.0	48.5	2290.0
Starch Potatoe	0.0	0.0	0.0	0.0	45.0	1250.0	45.0	1250.0
Alfalfa (1st year)	0.0	0.0	0.0	0.0	14.0	400.0	0.0	0.0
Alfalfa (2nd year)	0.0	0.0	0.0	0.0	14.0	220.0	0.0	0.0
Alfalfa (3rd year)	0.0	0.0	0.0	0.0	12.0	200.0	0.0	0.0
Miscanthus	8.1	496.1	8.1	496.1	8.1	496.1	16.3	496.1
Whole Plant Triticale	10.0	250.0	12.5	250.0	15.0	250.0	16.0	250.0
Switchgrass	10.5	148.9	10.5	148.9	8.8	148.9	17.5	148.9
Fiber Sorghum	0.0	0.0	8.0	250.0	6.0	250.0	14.0	250.0

Table 1
Yields (in dry matter tons/ha) and production costs (in €/ha) for food and energy crops, depending on the small agricultural region (SAR), part 1.

	SAR5		SAR6		SAR7	
	yield	production cost	yield	production cost	yield	production cost
Wheat (after Wheat)	7.4	380.0	6.9	375.0	6.7	290.0
Wheat (standard)	8.0	370.0	7.4	365.0	7.2	280.0
Wheat (after good preceding crop)	8.4	355.0	7.8	350.0	7.6	265.0
Spring Barley	6.1	305.0	5.5	250.0	6.0	230.0
Winter Barley	7.8	345.0	6.9	345.0	7.0	260.0
Rapeseed	3.5	368.0	3.3	370.0	3.0	270.0
Sunflower	3.0	280.0	3.0	280.0	2.5	280.0
Maize	9.5	430.0	8.0	400.0	9.0	400.0
Spring Pea	5.0	280.0	4.3	270.0	4.2	230.0
Winter Pea	4.3	258.0	4.3	245.0	4.0	230.0
Horsebean Pea	4.3	285.0	4.3	285.0	3.5	285.0
Sugar Beet	80.0	700.0	0.0	0.0	80.0	0.0
Food Potatoe	48.5	2290.0	0.0	0.0	0.0	0.0
Starch Potatoe	45.0	1250.0	0.0	0.0	0.0	0.0
Alfalfa (1st year)	13.0	400.0	0.0	0.0	0.0	0.0
Alfalfa (2nd year)	13.0	220.0	0.0	0.0	0.0	0.0
Alfalfa (3rd year)	9.0	200.0	0.0	0.0	0.0	0.0
Miscanthus	14.6	496.1	12.2	496.1	9.8	496.1
Whole Plant Triticale	15.0	250.0	14.0	250.0	14.0	250.0
Switchgrass	15.8	148.9	13.1	148.9	10.5	148.9
Fiber Sorghum	12.0	250.0	8.0	250.0	8.0	250.0

Table 2
Yields (in dry matter tons/ha) and production costs (in €/ha) for food and energy crops, depending on the small agricultural region (SAR), part 2.

	yield	production cost
SRC8	8	485.2
SRC10	10	571.2
SRC12	12	657.1

Table 3
Short Rotation Coppices' yields (in dry matter tons/ha/year) and production costs (in €/ha/ha).

	Low	Benchmark case	High
Wheat (after Wheat)	83.65	111.13	148.45
Wheat (standard)	83.65	111.13	148.45
Wheat (after good preceding crop)	83.65	111.13	148.45
Spring Barley	92.42	122.79	164.02
Winter Barley	77.93	103.53	138.31
Rapeseed	136.02	204.38	308.56
Sunflower	142.46	214.06	323.17
Maize	70.39	99.72	142.15
Spring Pea	94.91	126.08	168.43
Winter Pea	94.91	126.08	168.43
Horsebean Pea	97.25	129.20	172.60
Sugar Beet	32.99	32.99	32.99
Food Potatoe	136.74	136.74	136.74
Starch Potatoe	42.68	42.68	42.68
Alfalfa (1st year)	65.39	65.39	65.39
Alfalfa (2nd year)	65.39	65.39	65.39
Alfalfa (3rd year)	65.39	65.39	65.39

Table 4
Food crop prices for the "low", "benchmark", and "high" agricultural price scenarios (in €/ton).

	SAR1-2	SAR3-7		SAR1-2	SAR3-7
Wheat	6	9	Food Potatoe		19
Spring Barley	5	5	Starch Potatoe		19
Winter Barley	6	5	Alfalfa 1		2
Maize	3	3	Alfalfa 2		1
Rapeseed	8	6	Alfalfa 3		1
Sunflower	2	2	Miscanthus	0.3125	0.3125
Spring Pea	4.5	5	Switchgrass	0.375	0.3125
Winter Pea	4	5	Whole Plant Triticale	3	2
Horsebean Pea	7	6	Fiber Sorghum	2	2
Sugar Beet		6	Poplar SRC	0.0762	0.0762

Table 5
Average number of pesticide and herbicide treatments per crop, depending on the small agricultural region (SAR) (in number of treatments/ha/year)

	SAR1	SAR2	SAR3	SAR4	SAR5	SAR6	SAR7
Wheat	160	180	220	180	200	200	180
Spring Barley	100	125	135	120	125	120	130
Winter Barley	130	155	170	170	160	150.25	160
Maize	175	180	195	195	195	175	170
Rapeseed	50	50	50	50	50	50	50
Sunflower	140	140	145	160	150	140	150
Sugar Beet			130	130	100		
Food Potatoe			170	170	170		
Starch Potatoe			160	160	160		
Miscanthus	60	60	60	80	80	80	80
Switchgrass	100	100	120	120	120	120	120
Whole Plant Triticale	120	120	150	150	150	140	140
Fiber Sorghum		80	60	140	120	80	80

Table 6
Average nitrogen fertilisation level per crop, depending on the small agricultural region (SAR) (in uN/ha/year)

3.3 Forest data

First, the characteristics of the existing forest were determined. Secondly, the quantity of wood available per diameter category was assessed using the previous information. Thirdly, data dealing with harvest costs, conditioning costs, and prices were gathered for each category.

Harvest costs depend on the species, the diameter, the slope of the plots, and the distance to the nearest access road.

The French National Forest Survey (IFN) is the main data source for the forest feature in our model. In the IFN, each type of forest stand (e.g., high forest, coppice, etc.) is characterised by its age, the share of the different species (e.g., hardwood, softwood, and poplars), its wood volume, and its annual growth. Based on this information, a harvesting scenario is applied (e.g., thinning, improvement and regeneration cutting) that determines the gross annual harvestable wood volume and the types of harvestable products. Harvesting losses and wood volumes that are unharvestable due to technical logging difficulties or the reluctance of small private owners, are then deducted from the gross annual wood volume to obtain the net annual harvestable wood volume for each county. Harvesting costs (including felling cost, tree processing, and hauling costs), stumpage (the price to be paid to a land owner by an operator to harvest standing timber on his land) as well as wood prices were provided for Champagne-Ardenne by the French Association of Forest Cooperatives (Union des Coopératives Forestières de France, UCFF) and were harmonised with those from the French National Forestry Service (Office National des Forêts, ONF). Wood prices are provided in table 7. Examples of harvesting costs and stumpage are provided in appendix in tables 21 and 22.

Detailed information on forest data sources and processing can be found in appendix (c.f. table 16).

	Non-barked logs	Long-barked logs	Short-barked logs	Bundles	Wood chips
Softwood	120	48	63.6	55	53.0
Poplar	75	45		55	34.8
Hardwood	102.4	53		55	43.9

Table 7
Wood prices for non-energy use depending on the species and the conditioning (in €/ fresh ton).

	Switchgrass	Miscanthus	W.P. Triticale	Fiber Sorghum	Straw	Poplar SRC
LHV (MWh/ dry ton)	4.643	4.170	4.170	4.170	4.170	5.004
	Hardwood	Softwood	Poplar			
LHV (MWh/ std. ton) (moisture degree)	2.3107 (50%)	2.78856 (45%)	1.83177 (55%)			

Table 8
Lower heating values of the various lignocellulosic biomass sources, in MWh/tons, depending on their reference moisture degree.

3.4 Facility and demand data

In this study, we simulate the setting up of a second generation ethanol production facility. As mentioned above, the facility is characterized by its use of enzymatic hydrolysis and fermentation to produce bioethanol from lignocellulosic biomass, with a target production of 180 million liters of ethanol per year. This corresponds to an energy production equivalent to 1,064 10^6 MWh[5]. Given the current process energy efficiency of 0.39 (Schmidt et al., 2010) and a 7,000 hour/year workload hypothesis, the facility has a size of 389.8 MW (biomass input). This implies a demand for lignocellulosic feedstock equivalent to 2,728,612 MWh.

We use the lower heating values (LHV) of the various lignocellulosic biomass sources to convert tons into MWh (c.f. Table 8).

3.5 Transportation data

We use distances that minimize transportation time between counties, which is what road haulage contractors tend to do. Our distance matrix takes into account the road network and the topography (people drive faster on flat stretches than on hilly roads) as well as peak and off-peak hours. Transportation costs per ton and kilometre are calculated using the trinomial formula from the "French National Road Center" (Centre National Routier, CNR,2008 data), based on kilometric costs, hourly rates, and fixed costs as well as the type of vehicle which is being used. The choice of the vehicle depends on the type of biomass, its conditioning, the slope of the forest stand, and the distance to cover. For instance, a five-axle trailer truck transports straw bales over a long distance and a tractor transports them over a short distance (less than 25 km). In practice, costs also vary according to distance because the customer is required to pay for the return trip for short distances, whereas for longer distances the road haulage contractor pays for it.

[5]We assume ethanol has an energy content equivalent to 5.91 kWh/L, or 21 283 kJ/L.

	2007 observed data	2007 simulated data
Cereal crops	62.91%	70.97%
Oilseed crops	19.19%	16.27%
Protein crops	1.39%	2.86%
Sugar beet	9.47%	8.46%
Potatoes	1.68%	1.44%
Alfalfa	5.36%	0%

Table 9
Observed and simulated land-use share for the main crop categories, expressed in percentage of the represented utilised agricultural area.

Dedicated crop transportation costs per oven dry ton and kilometre, for each type of conditioning and the relevant vehicles, are provided in appendix in table 23 in the form of piecewise linear functions. Wood transportation costs per ton and kilometre for each type of conditioning and the relevant vehicles are provided in appendix in table 24 in the form of transportation cost functions. Detailed information on transportation data sources and processing can be found in appendix (c.f. table 16).

3.6 Validation

To validate our model, we compared the simulated regional land use to the observed 2007 situation in Champagne-Ardenne. The validation scenario entails maximizing the sum of counties gross margins, given the 2006 agricultural prices in the region, and subjected to constraints on the sugar beet, starch potatoes, and food potatoes areas at the *département* level. These crops are generally subjected to quotas and/or contracts and they require specific equipment. Their production is therefore quite stable over time. We compared our simulated land use to data for farms growing cereal, oilseed, and protein crops provided by the French agricultural bureau of statistics (Statistique Agricole Annuelle and Enquête structure 2007) at the *département* level, which is the smallest administrative level for which data are available. Table 9 shows that they are quite similar, except for alfalfa for which area is underestimated. This is often the case in micro-economic agricultural supply models, for farmers generally grow alfalfa for dehydration cooperatives in which they are shareholders.

4 Results

4.1 Individual biomass supply curves

4.1.1 Benchmark case

Fig. 4 shows that perennial crops have a higher energy supply potential than annual crops and wood in the Champagne-Ardenne region. Among dedicated crops, Switchgrass is the most promising in terms of quantity and cost (it is the second cheapest). Table 10 provides a comparison of the opportunity costs of the first MWh equivalent of biomass that is made available for the various lignocellulosic sources. It is noticeable that, apart from Fiber Sorghum, Miscanthus is the least profitable although currently in France it is the most highly cultivated. This finding highlights the importance and influence of the supply chain, and especially of the rhizomes providers.

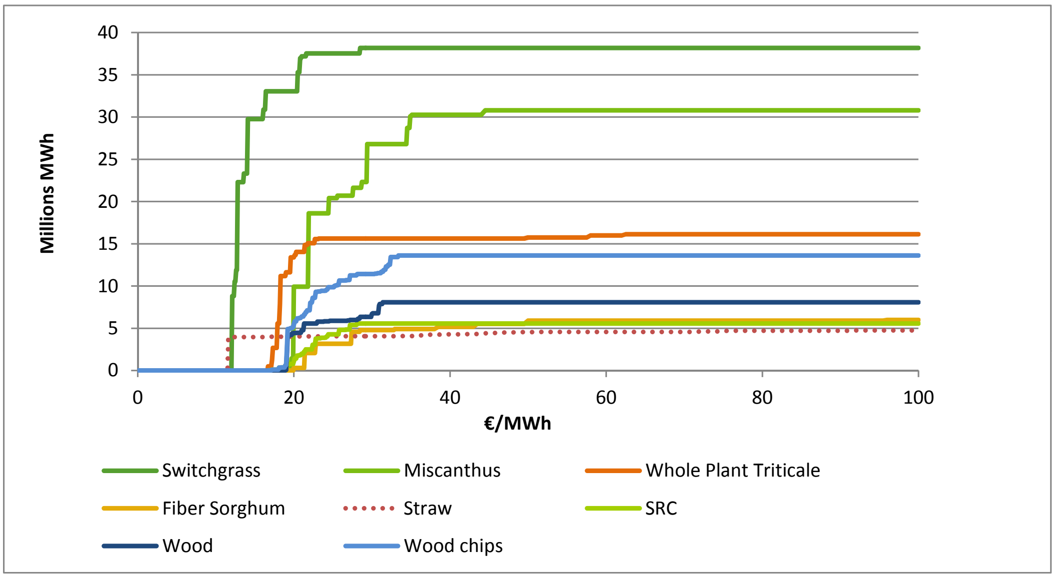


Fig. 4. Supply curve for each type of lignocellulosic biomass in the benchmark case.

Straw happens to be the cheapest biomass source, though with a limited potential. However, its opportunity cost, corresponding to its fertilising value in the model, is underestimated as it does not reflect farmers' willingness to supply their straw. The

	Opportunity cost of the first unit of biomass produced in the region (€/MWh)		
	Low	Benchmark	High
Miscanthus	17.1	19.7	24.9
Switchgrass	9.5	12.1	16.5
Whole Plant Triticale	12.4	16.7	22
Straw	11.6	11.6	11.6
Fiber Sorghum	14.7	20	28.3
Poplar SRC	13.7	16.8	21.1
Wood	19	19	19
Wood chips (from SRC and forest biomass)	13.7	16.8	19

Table 10
Comparison of the opportunity costs of the first MWh equivalent of each type of biomass produced in the region (in euro/MWh with a precision of 0.1 euro) and for three agricultural price scenarios. These opportunity costs correspond to the intersection of the supply curve with the X-axis.

latter has been investigated in a survey by Arvalis (ARVALIS/ONIDOL, 2009b), but was not accounted for in this study due to non-linearities and computer time issues.

It is generally advocated that there are millions of tons of wood remnants that are currently not harvested in France and are thus expected to help reach the renewable energy targets without hindering other wood uses (ADEME et al., 2009). Fig. 5 shows that energy and non-energy uses compete for wood that is already harvested. It can be seen that the total amount of harvested wood, no matter the use, remains nearly constant. It actually increases by 0.12% when wood starts to be used for energy purposes, which is due to an increase by 1.7% in the amount of small diameter branches harvested (i.e., remnants). Fig. 6 shows that small diameter branches as well as big diameter branches are used as energy sources. These results are consistent with the current situation. This can be explained by the fact that remnants are not currently harvested because it is not profitable, no matter the potential use, due, for instance, to accessibility issues that increase costs for instance. The types of conditioning chosen on-site are mainly wood chips and logs. This will imply extra costs to "chip" the logs at the biorefinery, if necessary. Table 11 provides details on the cost of wood per species and type of conditioning. Wood is diverted from its non-energy uses (timber, pulp and paper, etc.) from 19 €/MWh on, starting with softwood and hardwood small and medium diameter branches, conditioned into wood chips, bundles, and finally logs.

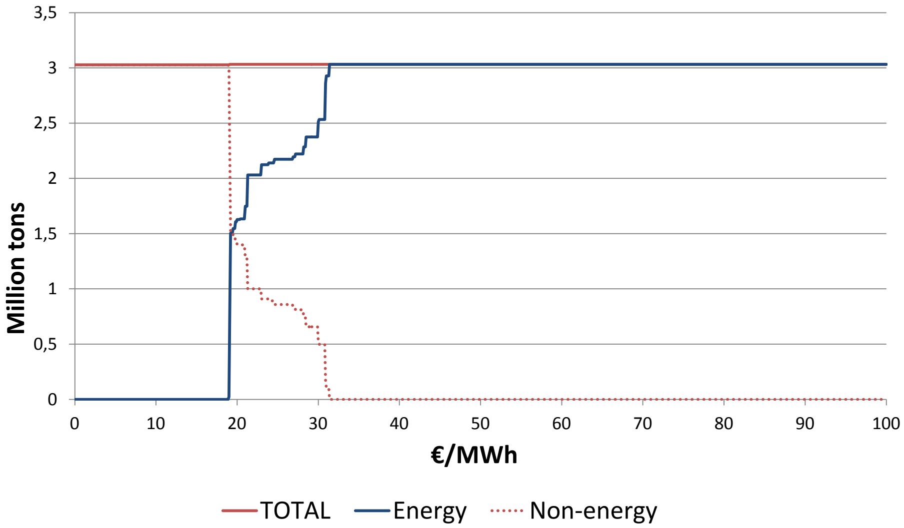


Fig. 5. Wood quantities (in fresh tons) dedicated to energy and non-energy uses depending on the price offered (in €/MWh equivalent).

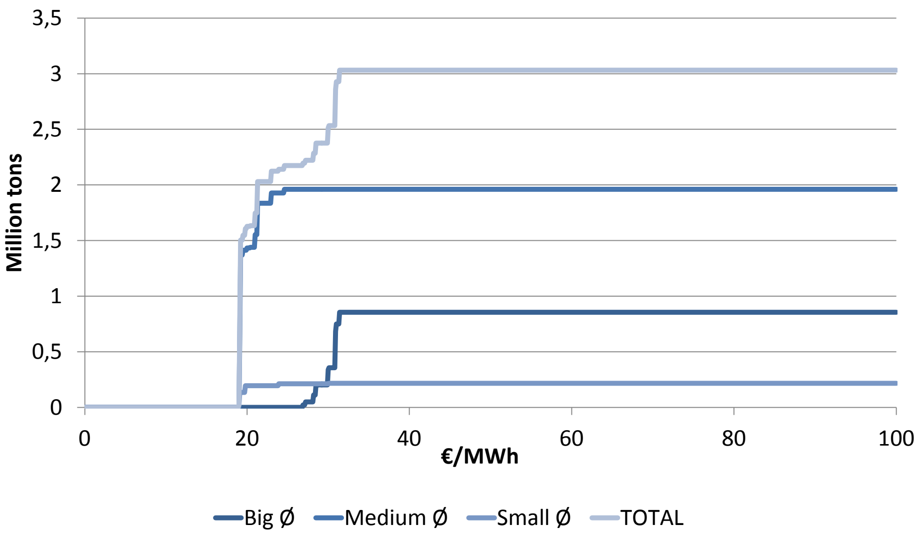


Fig. 6. Wood quantities (in fresh tons) sold for energy use per branch diameter (small, medium, big), depending on the price offered (in €/MWh equivalent).

	Opportunity cost of the first MWh harvested		
	Log	Bundle	Wood chips
Softwood	21	19.8	19.1
Hardwood	23	23.9	19
Poplar	24.6	30.1	*

Table 11
Opportunity costs of the first MWh of wood harvested for energy uses, detailed per species and type of conditioning (with a precision of 0.1 euro/MWh).

4.1.2 Impact of the agricultural prices economic context

The agricultural price context mainly influences the opportunity cost of lignocellulosic crops, while only marginally modifying their relative profitability. Switchgrass and Miscanthus remain respectively the cheapest and the most expensive dedicated crops. Wood supply is not influenced by the agricultural price context scenarios as we account for neither afforestation nor deforestation. Wood is thus more interesting in the case of high agricultural prices. Individual supply curves for the low and high agricultural price context are provided in figure 7 and 8.

4.2 Biomass supply curve (all biomass sources considered)

Individual supply curves provide insight in the potential supply and the related opportunity cost for each biomass type, and allow for comparisons (cf. Subsection 4.1.1). However, in practice, the various biomass sources will compete for the supply of energy feedstock and the various dedicated crops will also compete for agricultural land. As their yields and production costs vary from one small agricultural region to another, their relative profitability can vary accordingly. Due to the existence of fixed and variable production costs, the relative profitability of perennial dedicated crops also varies with the price paid per unit of energy content (in euro/MWh). For all these reasons, we expect that allowing for competition between the various biomass sources will increase the amount of lignocellusic feedstock supplied for a given price. In addition, it provides usefull information on the composition of the optimal feedstock mix that is made available for a given price.

4.2.1 Benchmark case

The results concerning the type and minimum opportunity cost of the biomass sources which compose the whole supply (see Fig. 10 and Table 12) are quite consistent with

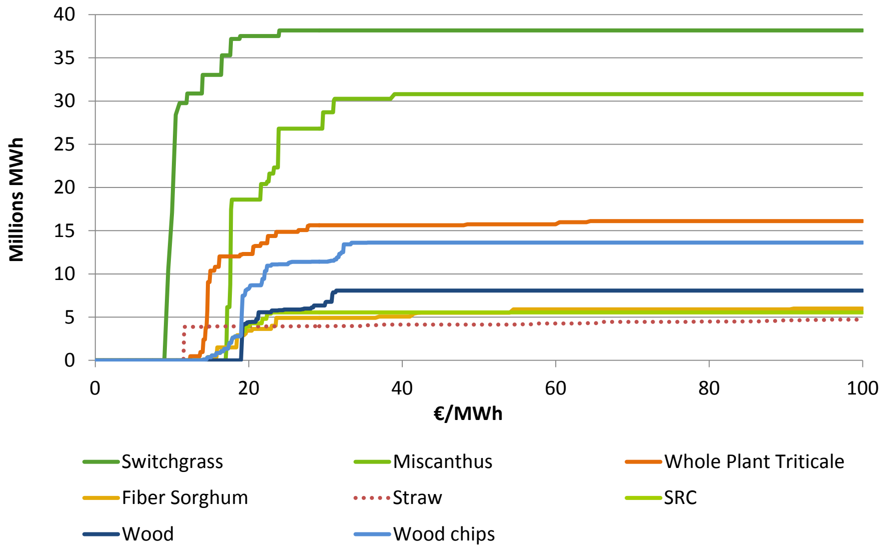


Fig. 7. Supply curve for each type of lignocellulosic biomass in the low agricultural price context (1st decile of 1993-2007 prices).

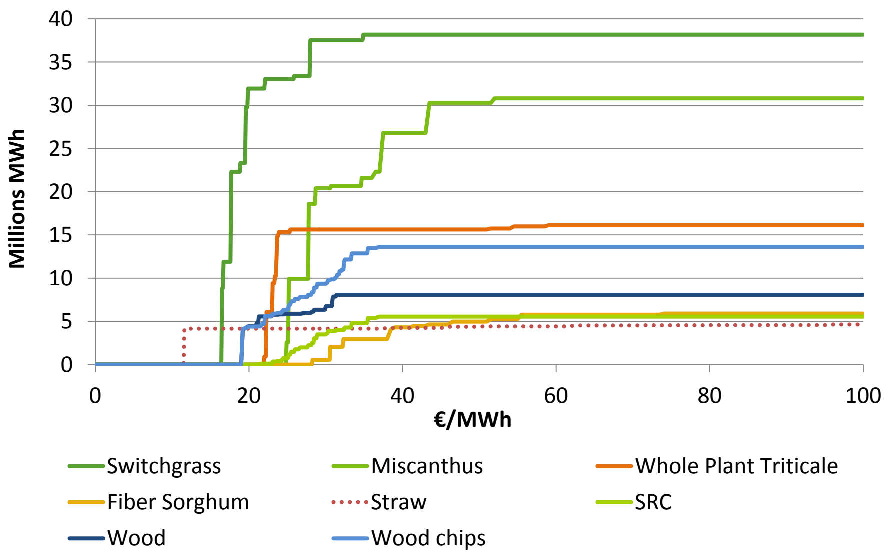


Fig. 8. Supply curve for each type of lignocellulosic biomass in the high agricultural price context (9th decile of 1993-2007 prices).

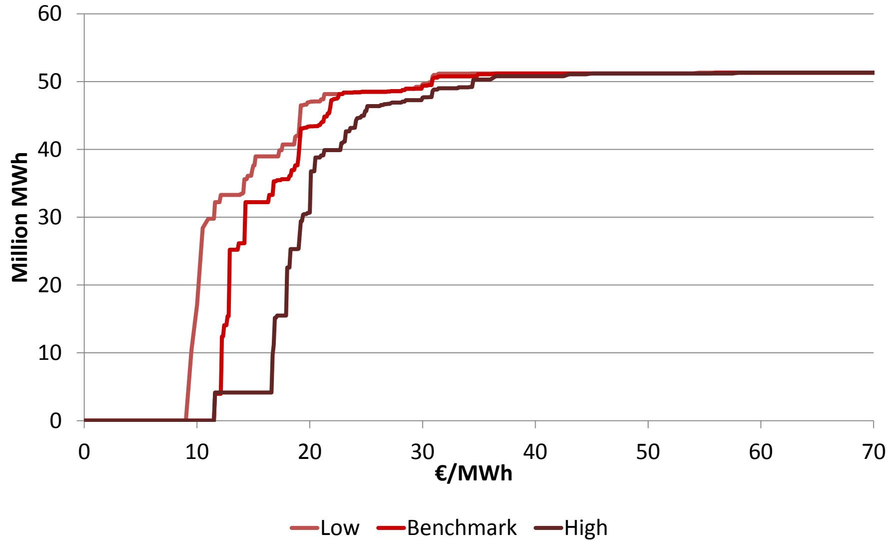


Fig. 9. Lignocellulosic biomass supply curves depending on the agricultural price context (low, benchmark, high).

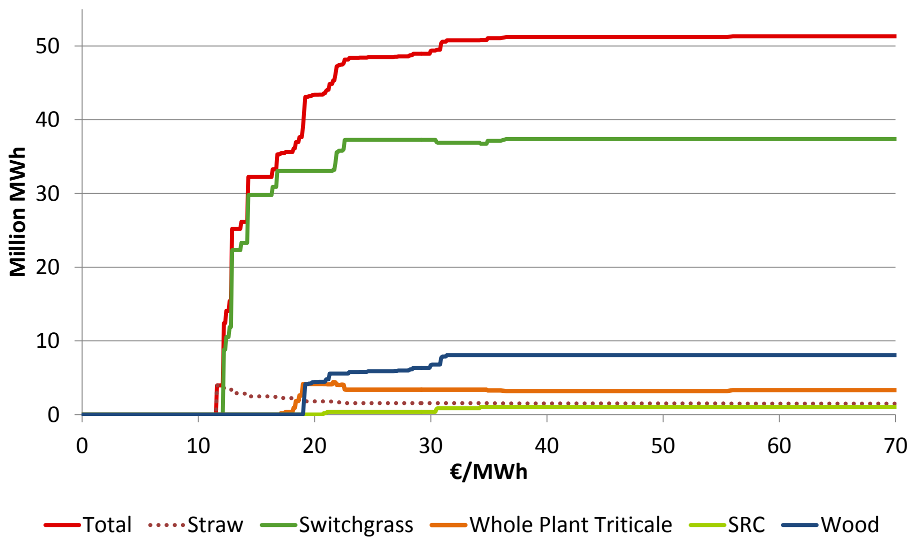


Fig. 10. Detail of the lignocellulosic biomass mix supplied in the benchmark case.

those presented in the section "individual supply curves". That is to say, the first and cheapest biomass source is straw, for it is a by-product of cereal crops in the model and is given a production cost only worth its fertilising value. It is quickly followed by Switchgrass for a minimum price of 12.2 €/MWh, whose supply reaches a plateau for prices over 22.6 €/MWh. Whole plant triticale is grown and supplied for prices over 17.1 €/MWh, though it is less profitable than Switchgrass. This is explained by the validation constraints: they impose areas in sugar beets and potatoes and these crops are included in crop rotations in which whole plant triticale can be substituted for barley. Validation contraints also explain the fact that perennial crops are limited to 66% of the regional UAA. Most surprisingly, Switchgrass is not the only perennial crop supplied as poplar SRC is provided for minimum prices of 20.8 €/MWh. Despite higher energy yields per hectare, SRC is less profitable than switchgrass because it has higher fixed establishment costs. However, this only holds true until prices reach 30.6€/MWh. In that case, SRC is substituted for Switchgrass, but only to a certain extent because agropedoclimatic conditions restrict areas suitable for cultivating SRC.

Perennial lignocellulosic crops are commonly expected to be grown on the less fertile agricultural land and thus not in competition with food crops. However, our results show that it is not the case, at least in the Champagne-Ardenne region, where Switchgrass and Miscanthus have the highest yields on SARs 4 to 6, which are among the most fertile and profitable SARs for food crops. Fig. 11 shows that they are not grown at first on the least fertile and profitable areas [6].

Though decreasing on average in the Champagne-Ardenne region, the number of pesticides and herbicides treatments can increase in some SARs for some price ranges (see figures 12 and 13 respectively) due to indirect land use change in the region. E.g., the average number of treatments per hectare increases for MWh prices ranging from 12.4 to 18.6 €/MWh in SAR3, which corresponds to a rotation substitution leading to a decrease in alfalfa area and an increase in wheat, rapeseed and beetroot area, the latter being more treated.

4.2.2 Impact of the agricultural price economic context

The agricultural price context impacts the minimum price for which lignocellulosic biomass is supplied in the case of low prices (9.5 €/MWh instead of 11.6€/MWh). It also impacts the amount of biomass supplied for a given price, until a threshold of 58 €/MWh for which an identical maximum amount of 51,310,813.5 MWh is reached (c.f. Fig. 9). The agricultural price context has an impact on the biomass supply location, as far as SARs

[6]SAR1 and SAR2 are the least profitable areas for food crops, SAR6 and SAR7 are intermediate and SAR3 to 5 are the most profitable

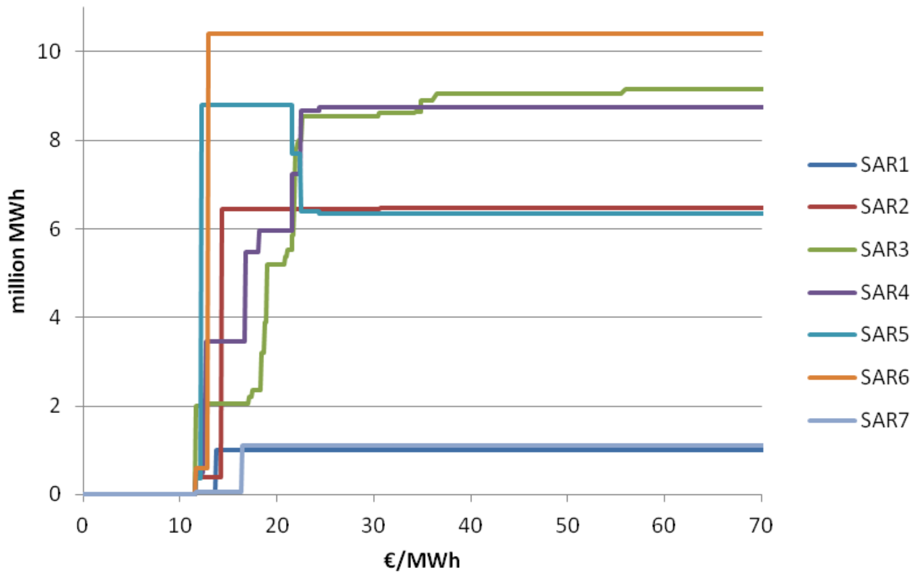


Fig. 11. Detail of the amount of biomass supplied by each Small Agricultural Regions in the benchmark case (in million MWh).

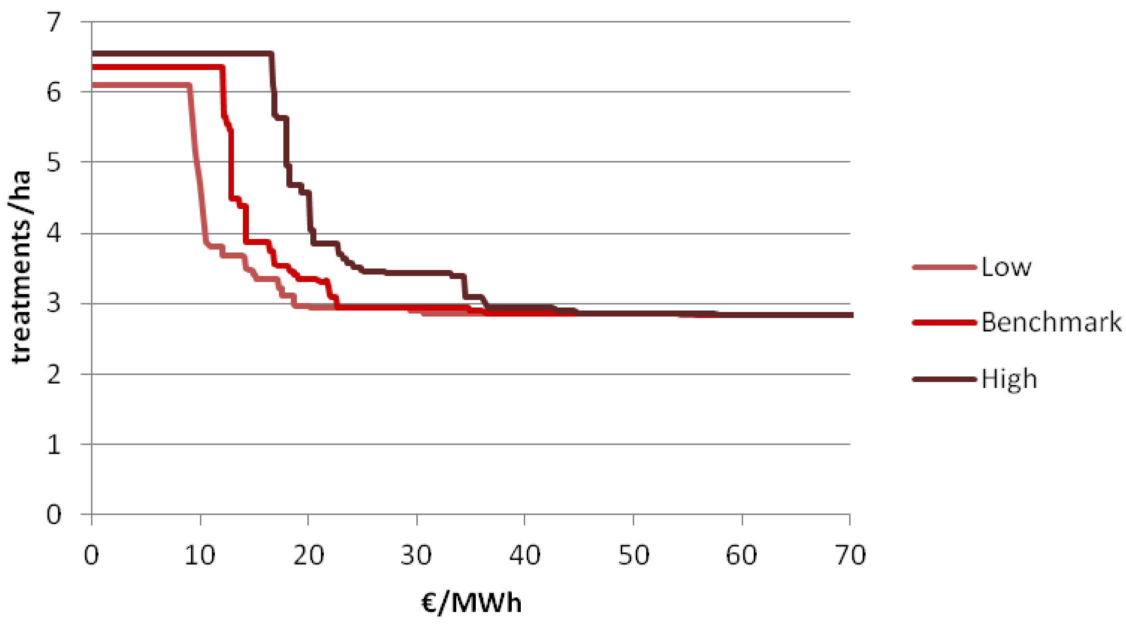


Fig. 12. Average number of pesticides and herbicides treatments per hectare in the region, depending on the agricultural prices context.

are concerned, especially in the high price context (see figures 19a and 19b in appendix). Details on the biomass mix composition are provided in appendix in figures 20a and 20b.

The opportunity costs of the first MWh provided for each biomass source is generally higher when there is competition between the biomass sources (c.f. Table 12 in compar-

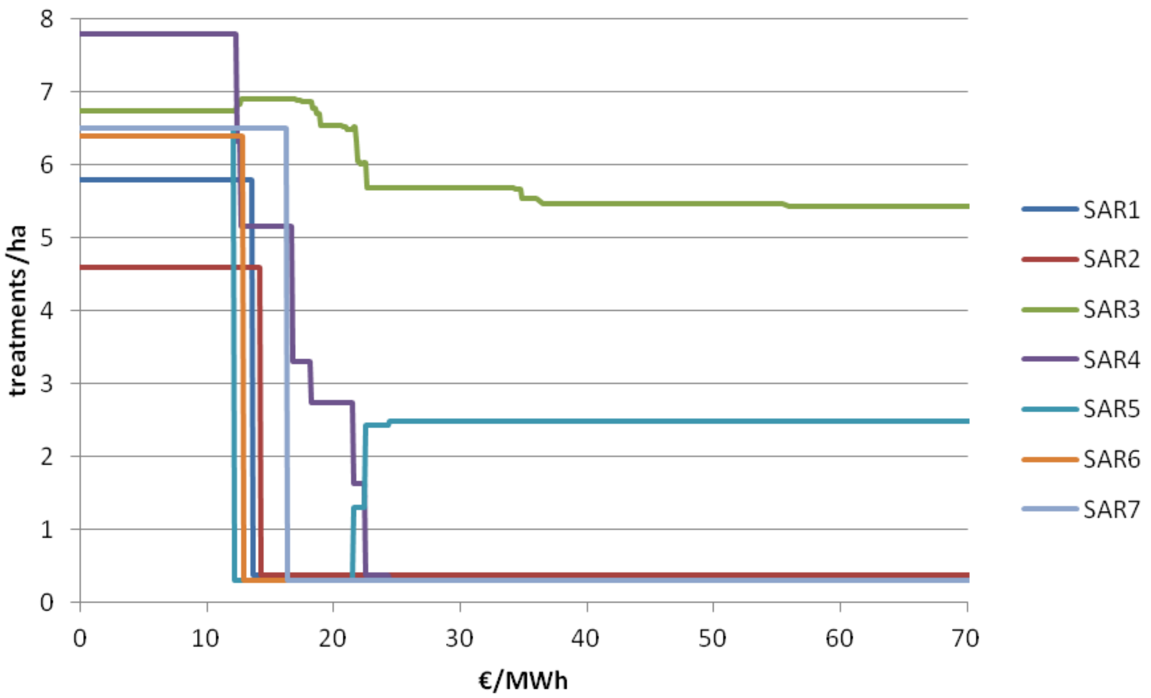


Fig. 13. Average number of pesticides and herbicides treatments per hectare in each Small Agricultural Regions, in the benchmark case.

ison with Table 10). However, except for whole plant triticale and SRC in the high price context, biomass sources have the same order of appearance.

4.3 Bioenergy facility siting

Comparing the results for a facility's demand for biomass equivalent to 2 728 612 MWh with the results from the previous subsection for the same demand level, enables us to investigate the impact of facility location on the choice of biomass to be grown, the supply cost, and the potential environmental impacts. The facility's demand represent circa 5.3% of the total amount of lignocellulosic biomass that can be supplied by the region, based on Section 4.2.

4.3.1 Benchmark case

In the benchmark case, the facility is located in county 5110 and is supplied with 362 763 oven dry tons of straw (39% of the total exportable straw in the region) and 261 876 oven dry tons of switchgrass silage. Switchgrass silage comes from the county where the facility is located and straw comes from 29 different counties (see figure 15). The opportunity cost of the last MWh of biomass delivered to the facility (i.e., switchgrass

	Low	Benchmark	High
Cereal Straw	11.6	11.6	11.6
Switchgrass	9.5	12.2	16.7
Whole plant Triticale	13.9	17.1	23.2
Miscanthus	*	*	*
Fiber Sorghum	*	*	*
Poplar SRC 12	19.2	20.8	26.6
Poplar SRC 10	30.5	30.5	33.2
Poplar SRC 8	*	*	*
Softwood	19.1	19.1	19.1
Hardwood	19	19	19
Poplar	24.6	24.6	24.6

Table 12
Opportunity costs of the first MWh equivalent of each type of biomass entering the biomass mix produced in the region, depending on the agricultural price context (in euro/MWh with a precision of 0.1 euro).

from SAR4) is 12.703€/MWh and includes a 5.167 € production and conditioning cost, 7.5€ of foregone revenue due to crop rotation substitution, and a 0.036€ intra-county transportation cost.

Based on the regional supply curve (Section 4.2), the opportunity cost of supplying 2 728 612 MWh is 11.511 €/MWh in the benchmark case. The biomass mix is composed only of straw bales (654 343 tons, i.e., 69% of the total exportable straw) supplied by 82 counties and mainly from SAR3 (see figure 14). The level of pesticide and herbicide treatments (figure 16b) as well as nitrogen fertilisation (figure 17b) remain the same compared to a situation without biomass supply (figure 16c and figure 17c respectively).

When facility siting and transportation are accounted for, the composition of the biomass mix is modified, the dedicated biomass production is concentrated in fewer counties, and its opportunity cost increases. Biomass is supplied from fewer SARs (3-4-5-7), and mainly from SAR4 and SAR3. The nitrogen fertilisation level increases slightly whereas the number of treatments decreases slightly, on average at the region level (see figures 17a and 16a for maps). However, at the local level, the average fertilisation and herbicide and pesticide treatments levels increase for some counties.

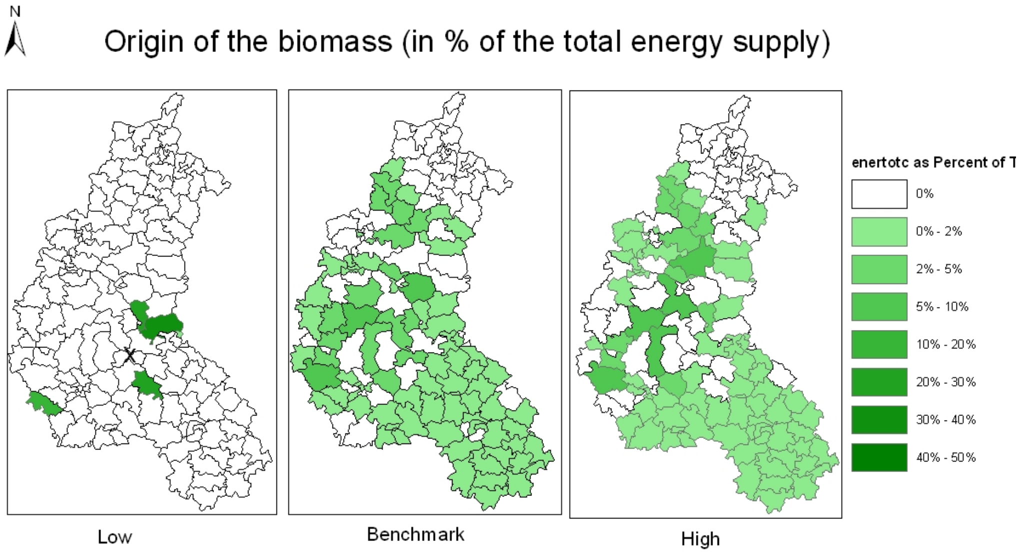


Fig. 14. Biomass supply per county for the various agricultural prices scenarios ("low", "benchmark", and "high") when there is no facility to be located (in percentage of total supply in primary energy content).

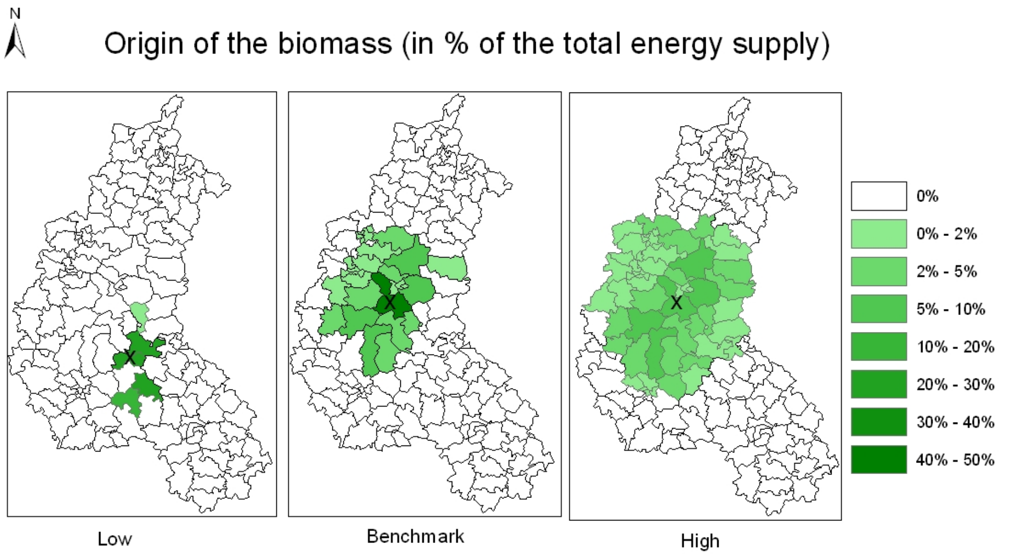


Fig. 15. Facility location (X) and biomass supply per county (percentage of total supply in primary energy content) for the various agricultural prices scenarios : "low", "benchmark", and "high".

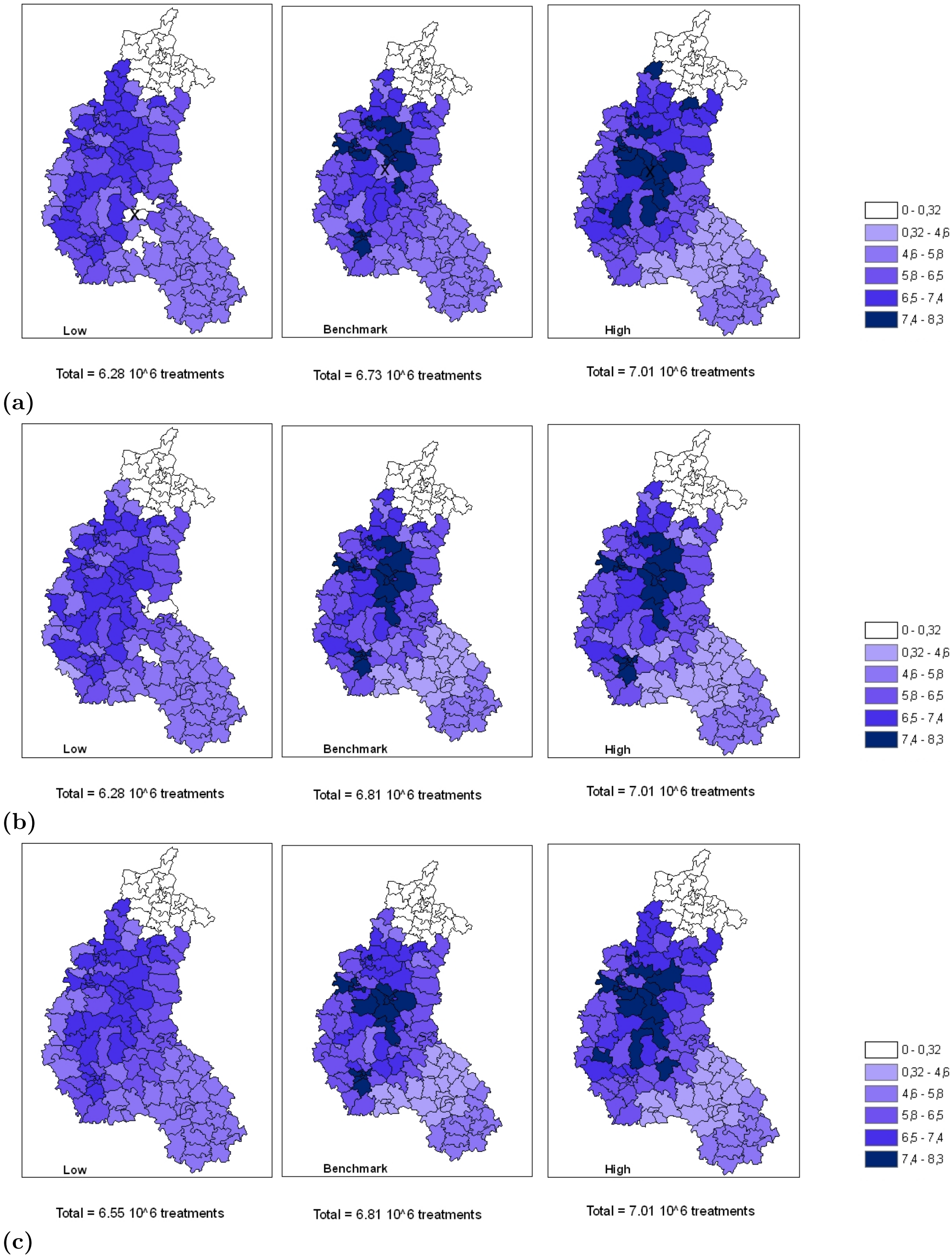


Fig. 16. Average number of herbicide and pesticide treatments per county (in treatments /ha) depending on the agricultural price context ("low", "benchmark", "high") for three scenarios : **(a)** biomass demand with facility location, **(b)** biomass demand with no facility, **(c)** no biomass demand.

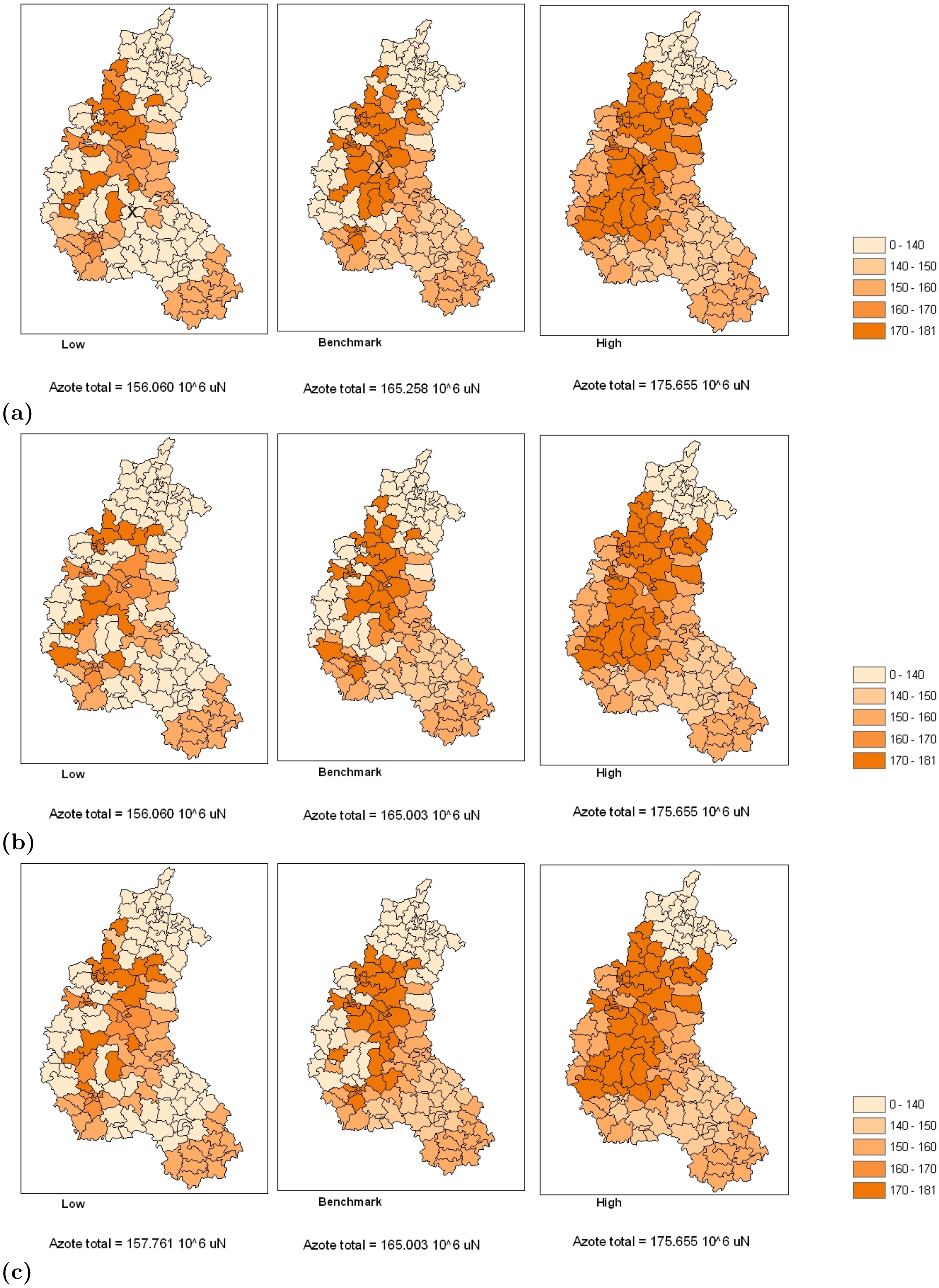


Fig. 17. Average nitrogen fertilisation level per county (in N units /ha) depending on the agricultural price context ("low", "benchmark", "high") for three scenarios : **(a)** biomass demand with facility location, **(b)** biomass demand with no facility, **(c)** no biomass demand.

4.3.2 Impact of the "Low" agricultural prices economic context

In the case of "low" agricultural prices, the facility is located in another county "1008" and is supplied with 587 683 o.d. tons of switchgrass silage, arriving from 5 different counties belonging to SAR6 (see figure 15). The opportunity cost of the last MWh of biomass delivered to the facility (i.e., switchgrass from county 5133) is 11.055 €/Mwh and includes a 5.778 € production and conditioning cost, 3.52€ of foregone revenue due to crop rotation substitution, and a 1.757€ transportation cost to the facility.

Based on the regional supply curve, the opportunity cost of supplying 2 728 612 MWh is 9.299 €/MWh in the low price context case. The biomass mix is composed only of silage Switchgrass (587 683 tons dry matter) supplied by 5 counties belonging to SAR6. The number of pesticide and herbicide treatments (figure 16b) as well as the nitrogen fertilisation level (figure 17b) decrease in the region, compared to a situation without biomass supply (figure 16c and figure 17c respectively).

When facility siting and transportation are accounted for, the composition of the biomass mix remains the same. However, though still belonging to SAR6, the producing counties differ. In addition, the opportunity cost of the switchgrass supplied increases. The nitrogen fertilisation level and the number of treatments remain the same on average at the region level (see figures 17a and 16a for maps). However, at the local level, the average fertilisation and herbicide and pesticide treatments levels increase for some counties.

4.3.3 Impact of the "high" agricultural prices economic context

In the case of "high" agricultural prices, the facility is still located in county "5110", but is only supplied with straw (654,343 o.d. tons) arriving from 53 different counties (see figure 15). Straw is mainly harvested on SAR3 and represent 66% of the total amount of exportable straw in the region. The opportunity cost of the last MWh of straw delivered to the facility is 13.028 €/Mwh and includes a 11.51 € production and conditioning cost and a 1.517€ transportation cost to the facility.

Based on the regional supply curve, the opportunity cost of supplying 2 728 612 MWh is 11.511 €/MWh in the high price context case. The biomass mix is composed only of straw bales (654343 tons, i.e., 66% of the total exportable straw) supplied by 80 counties and mainly from SAR3. The level of pesticide and herbicide treatments (figure 16b) as well as nitrogen fertilisation (figure 17b) are the same compared to a situation without biomass supply (figure 16c and figure 17c respectively).

When facility siting and transportation are accounted for, the composition of the biomass mix remains the same, the dedicated biomass production is concentrated in fewer counties, and its opportunity cost increases. Biomass is supplied from less SARs (3-4-5-6-7), though still mainly from SAR3. The nitrogen fertilisation level and the number of treatments remain the same on average at the region level (see figures 17a and 16a for maps). However, at the local level, the average fertilisation and herbicide and pesticide treatments levels increase for some counties.

5 Conclusion and Discussion

Within an overall project to assess the competitiveness and environmental impacts of the production of bioenergy from lignocellulosic biomass, we set out in this particular study to investigate facility location, land allocation, biomass supply costs, and some environmental impacts in relation to the demand for lignocellulosic feedstock at the regional (Nuts 2) level.

For that purpose we developed a spatially-explicit regional supply model with a county sub-level to deal with the case of agricultural and forest lignocellulosic biomass. It accounts for land-use competition, transportation costs and the optimal location of bioenergy facilities as well as the competition between biomass sources and between their potential uses.

To illustrate our approach, we applied the model to the case of the French Champagne-Ardenne region. We generated the first lignocellulosic biomass supply curves for France and examined the type, quantity, opportunity cost and location of the biomass supplied, depending on the food crops price context.

Our results show that the Champagne-Ardenne region can provide up to 51.3 million MWh equivalent of lignocellulosic biomass, for a maximum opportunity cost of 58 euro/MWh [7]. The regional biomass mix is mainly composed of Switchgrass and to a lesser extent wood. This confirms that in this region dedicated energy crops can contribute to biomass production for bioenergy uses.

In addition, our results show that dedicated crop cultivation can increase environmental pressure on the local level, due to direct and indirect land-use substitution. We assessed the level of pesticide and herbicide as well as nitrogen fertiliser use at the county, Small Agricultural Region (SAR), and region levels. Although dedicated crop cultivation tend to decrease their use on average at the region level, it is not always the case at the county or SAR level. This can occur due to direct land use change because some

[7] Most of this maximum biomass supply is reached around 25 euros/MWh

dedicated crops have higher input levels than the crops to which they substitute. For instance whole plant triticale is more fertilised than barley, to which it substitutes in crop rotations. Or when the demand for straw increases, rotations with a higher share of cereal crops substitute to other, less input-intensive, rotations. Increased environmental pressure can also occur due to indirect land use change, when dedicated crop cultivation modify the location of other crops. In our study, it is the case for sugar beet and potatoe for instance, because we impose constraints on their area at the *département* level to reflect the fact that these crops are generally subjected to quotas and/or contracts.

Facility location has an impact on the type, cost and location of the biomass supplied, due to tradeoffs between "farm gate" supply costs and transportation costs. Compared to the same non-spatialised demand, facility location concentrates lignocellulosic feedstock production in fewer couties. Moreover, we show that foregone revenues incurred by land-use substitution play a major role in the supply cost of dedicated lignocellulosic crops. This clearly emphasizes the importance of accounting for land-use competition and substitution to accurately address the sustainability (competitiveness and environmental impacts) of lignocellulosic biomass production.

Our results also show that three well-accepted claims about the production and supply of lignocellulosic biomass in France do not hold true countrywide. First, although Miscanthus is the most frequent dedicated perenial crop in France today, it is not the most profitable dedicated crop in the Champagne-Ardenne region. We have found that Switchgrass has lower opportunity costs, a finding consistent with a study carried out by Bocquého and Jacquet (2010). Second, perennial lignocellulosic crops are commonly expected to be grown on less fertile agricultural land, thereby not coming into competition with food crops. However, our results show that this is not the case in Champagne-Ardenne where they would be at first grown in counties with the most fertile and profitable lands and not on marginal land. Switchgrass and Miscanthus actually have the highest yields on soil types which are the most fertile and profitable ones for food crops too. Finally, it is expected that forest remnants, which are not currently exploited, will be massively used for energy purposes. However, we show that remnants are not the providential biomass source they are expected to be. In fact, remnants are used if and only if prices are high enough to make them profitable. Therefore, energy and non-energy uses will continue to compete for wood that is harvested.

6 Perspectives

Our approach could undergo further development. First, the modeling of necessary logistics could be refined. Due to the huge volumes of biomass to be transported and the need to supply the facility all year long, the scheduling of biomass collection and storage play an important role in the competitiveness of lignocellulosic bioenergy chains. Second, surveys on the willingness of producers (farmers, forest owners and managers) to offer biomass were carried out in the framework of the project (ARVALIS/ONIDOL, 2009b; FCBA, 2009). Looking to avoid mass production of new crops in a given county, it would be interesting to integrate these results to better account for the behaviour of producers.

By using such a methodology, we should be able to more accurately predict the contribution of the agricultural and forest sectors to the potential biomass supply, and to provide investors and policy makers with insights into how best to envision the contribution of lignocellulosic biomass to renewable energy projects.

The presented methodology also constitutes a good basis to further investigate the environmental impacts of lignocellulosic biomass production and supply, in relation to its spatial distribution. These impacts are, for instance, variations in nitrogen fertilisation, greenhouse gas emissions linked to the biomass production and delivery, or the impacts of land-use changes on landscape and biodiversity. Moreover this spatially explicit approach could serve as a means to improve bioenergy production life cycle analyses (LCAs[8]). Since such an approach provides crucial information on the production side, i.e., on soils, cropping practices and especially land-use changes, it is expected that it will allow us to carry out consequential LCAs.

By further investigating the environmental impacts of biomass production and supply, in an integrated modelling framework, we will be able to determine if there is a need for public policies to mobilize this biomass potential in an environmentally-friendly way. If yes, this modelling framework will help us design the appropriate policies.

[8]First LCAs for the test region were performed during the project, see Gabrielle (2009)

References

ADEME, IFN, FCBA and SOLAGRO (2009). *Biomasse forestière, populicole et bocagère disponible pour l'énergie à l'horizon 2020.* Technical report, Etude réalisée pour le compte de l'ADEME , contrat n°0601C0134.

ARVALIS (2007). *L6 Données technico-économiques des cultures alimentaires actuelles.* Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

ARVALIS/ONIDOL, G. (2009a). *L4 Données technico-économiques des cultures ligno-cellulosiques par canton et contexte pédo-climatique.* Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

ARVALIS/ONIDOL, G. (2009b). *L8-1 Estimation de la disposition à offrir des producteurs (paille et cultures énergétiques).* Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Ballarin, A., Vecchiato, D., Tempesta, T., Marangon, F. and Troiano, S. (2011). Biomass energy production in agriculture: A weighted goal programming analysis. *Energy Policy*, 39(3), 1123–1131.

Bamière, L. et al. (2007). *L1 Typologie des cantons de la région-test.* Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Berndes, G., Hoogwojk, M. and van den Broek, R. (2003). The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass and Bioenergy*, 25(1), 1–28.

Bocquého, G. and Jacquet, F. (2010). The adoption of switchgrass and miscanthus by farmers: impacts of liquidity constraints and risk preferences. *Energy Policy*, 38(5), 2598–2607.

EEA (2006). *How much bioenergy can Europe produce without harming the environment?* Report 7/2006, European Environment Agency.

Ericsson, K. and Nilsson, L. (2006). Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass and Bioenergy*, 30(1), 1–15.

FCBA (2009). *L8-1 Estimation de la disposition à offrir des producteurs (bois et TCR).* Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Fischer, G., Prieler, S., van Velthuizen, H., Berndes, G., Faaij, A., Londo, M. and de Wit, M. (2010). Biofuel production potentials in europe: Sustainable use of cultivated land and pastures, part ii: Land use scenarios. *Biomass & Bioenergy*, 34(2), 173–187.

Gabrielle, B. (2009). *L7 Impacts environnementaux de la production des ressources ligno-cellulosiques*. Technical report, Report of the ECOBIOM project (ANR-05-BIOE-018).

Guindé, L., Jacquet, F. and Millet, G. (2008). Impacts du développement des biocarburants sur la production française de grandes cultures. *Review of Agricultural and Environmental Studies*, 89(4), 55–81.

Hellmann, F. and Verburg, P. (2011). Spatially explicit modelling of biofuel crops in Europe. *Biomass and Bioenergy*, 35(6), 2411–2424.

van der Hilst, F., Dornburg, V., Sanders, J. P. M., Elbersen, B., Graves, A., Turkenburg, W. C., Elbersen, H. W., van Dam, J. M. C. and Faaij, A. P. C. (2010). Potential, spatial distribution and economic performance of regional biomass chains: The north of the netherlands as example. *Agricultural Systems*, 103(7), 403–417.

Leduc, S., Schmid, E., Obersteiner, M. and Riahi, K. (2009). Methanol production by gasification using a geographically explicit model. *Biomass & Bioenergy*, 33(5), 745–751.

Lensink, S. and Londo, M. (2010). Assessment of biofuels supporting policies using the biotrans model. *Biomass and Bioenergy*, 34(2), 218–226.

Londo, M., Lensink, S., Wakker, A., Fischer, G., Prieler, S., van Velthuizen, H., de Wit, M., Faaij, A., Junginger, M., Berndes, G., Hansson, J., Egeskog, A., Duer, H., Lundbaek, J., Wisniewski, G., Kupczyk, A. and Konighofer, K. (2010). The refuel eu road map for biofuels in transport: Application of the project's tools to some short-term policy issues. *Biomass & Bioenergy*, 34(2), 244–250.

Petersen, J. (2008). Energy production with agricultural biomass: environmental implications and analytical challenges. *European Review of Agricultural Economics*, 35(3), 385–408.

Rozakis, S. and Sourie, J.-C. (2005). Micro-economic modelling of biofuel system in France to determine tax exemption policy under uncertainty. *Energy Policy*, 33(2), 171–182.

Scarlat, N. and Dallemand, J.-F. (2011). Recent developments of biofuels/bioenergy sustainability certification: A global review. *Energy Policy*, 39(3), 1630–1646.

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. and Schmid, E. (2010). Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies. *Applied Energy*, 87(7), 2128–2141.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu, T.-H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319(5867), 1238–1240.

Sourie, J., Tréguer, D. and Rozakis, S. (2005). *L'ambivalence des filières biocarburants.* Technical Report 2, INRA Sciences Sociales.

Tittmann, P. W., Parker, N. C., Hart, Q. J. and Jenkins, B. M. (2010). A spatially explicit techno-economic model of bioenergy and biofuels production in california. *Journal of Transport Geography*, 18(6), 715–728.

Ugarte, D. G. D. and Ray, D. E. (2000). Biomass and bioenergy applications of the polysys modeling framework. *Biomass & Bioenergy*, 18(4), 291–308.

de Wit, M. and Faaij, A. (2010). European biomass resource potential and costs. *Biomass & Bioenergy*, 34(2), 188–202.

Zilberman, D., Hochman, G., Rajagopal, D., Sexton, S. and Timilsina, G. (2013). The impact of biofuels on commodity food prices: Assessment of findings. *American Journal of Agricultural Economics*, 95(2), 275–281.

7 Appendix Model equations

$$\max_{X_i, LBD_{i,j}, (locus_j)} \sum_i \left(\Pi_i^{CROPS}\left(S_i^{ROT}\right) + \Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) + \right.$$
$$\left. + \Pi_i^{ENERGY}\left(X_i^{ENERGY}\right) \right) - \sum_{i,j} T_{i,j}^{ENERGY}\left(LBD_{i,j}^{ENERGY}\right) \cdot locus_j \quad (20)$$

subject to

$$\sum_{r,s} S_{r,s,i}^{ROT} \leq UAA_i, \quad \forall i \quad (21)$$

$$X_{c,s,i}^{CROPS} = \sum_r \left(y_{c,s} \cdot \gamma_{c,r} \cdot S_{r,s,i}^{ROT} \right), \quad \forall c, s, i \quad (22)$$

$$X_i^{EStraw} \leq \sum_{r,s} \left(\alpha_i \cdot y_{c,i}^{straw} \gamma_{c,r} \cdot S_{r,s,i}^{ROT} \right), \quad \forall i \quad (23)$$

$$W_i^{WOOD} \leq \overline{W_i^{WOOD}}, \quad \forall i \quad (24)$$

$$\rho \cdot \left(X_i^{NEWood} + X_i^{EWood} \right) \leq W_i^{WOOD}, \quad \forall i \quad (25)$$

$$X_i^{ECrop} + X_i^{EWood} + X_i^{EStraw} = X_i^{ENERGY}, \quad \forall i \quad (26)$$

$$X_i^{ENERGY} \geq \sum_j LBD_{i,j}^{ENERGY}, \quad \forall i \quad (27)$$

$$\sum_i LBD_{i,j}^{ENERGY} \cdot lhv^{ENERGY} = D^{ENERGY} \cdot locus_j, \quad \forall j \quad (28)$$

$$W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood} \geq 0, \quad \forall i \quad (29)$$

$$S_{r,s,i}^{ROT} \geq 0, \quad \forall r, s, i \quad (30)$$

$$LBD_{i,j}^{ENERGY} \geq 0, \quad \forall i, j \quad (31)$$

Constraint 21 sets that the areas grown with rotations including food and/or energy crops must be less than the total agricultural area in each county. Constraint 22 links crops production to the area dedicated to the various crop rotations. Constraint 23 relates the amount of straw that can be used for energy purpose to the area grown with cereal crops, and limits it to the share that can be exported without harming the soil organic matter content. Constraint 24 and 25 limits the amount of wood that is harvested for energy and non-energy uses to the amount available annually. We assume here that agricultural and forest areas are independent, i.e., deforestation and afforestation are not allowed, and that short rotation coppices (SRC) can only be grown on agricultural areas.

The lignocellulosic feedstock supply in each county X_i^{ENERGY} equals the sum of its annual and perennial dedicated crops X_i^{ECrop}, cereal straw X_i^{EStraw}, and wood X_i^{EWood} supply (26). A county i cannot export more lignocellulosic feedstock to other counties j

than its own production (27). The total amount of lignocellulosic biomass delivered to a county j must satisfy the facility's demand, if it exists (i.e. $locus_j = 1$) (Equation (28)).

Agricultural biomass equations

$$\Pi_i^{CROPS}\left(S_i^{ROT}\right) = \sum_{c,s}\left(\left(p_c \cdot y_{c,s} - c_{c,s}^{prod}\right) \cdot \sum_r \gamma_{c,r} \cdot S_{r,s,i}^{ROT}\right) \tag{32}$$

$$\Pi_i^{ENERGY}\left(X_i^{ECrop}\right) = \sum_c \left(\left(p^{MWh} \cdot lhv_c - c_c^{cond}\right) \cdot X_{c,i}^{ECrop}\right) \tag{33}$$

$$\Pi_i^{ENERGY}\left(X_i^{EStraw}\right) = \left(p^{MWh} \cdot lhv_{straw} - c_{straw}^{cond}\right) \cdot X_i^{EStraw} \tag{34}$$

Forest biomass equations

$$\Pi_i^{WOOD}\left(W_i^{WOOD}, X_i^{NEWood}, X_i^{EWood}\right) = \sum_{w,cond}\left(p^{wood} \cdot X_{w,cond,i}^{NEWood}\right) - \\ - \sum_{w,cond}\left(c_{w,cond}^{stump} \cdot W_{w,cond,i}^{WOOD} + c_{w,cond}^{harv} \cdot \left(X_{w,cond,i}^{NEWood} + X_{w,cond,i}^{EWood}\right)\right) \tag{35}$$

$$\Pi_i^{ENERGY}\left(X_i^{EWood}\right) = \sum_w p^{MWh} \cdot lhv_w \cdot X_{w,i}^{EWood} \tag{36}$$

Agricultural and woody biomass transportation equations

$$T_{i,j}^{ECrops}\left(LBD_{c,i,j}^{ECrops}\right) = \sum_{c,cond,vcl}\left(t_{c,cond,vcl,i,j} \cdot LBD_{c,cond,vcl,i,j}^{ECrops}\right) \tag{37}$$

with :

$$t_{c,cond,vcl,i,j}^{ECrop} = \delta_{c,cond,vcl,cld} \cdot d_{i,j} + \epsilon_{c,cond,vcl,cld} \tag{38}$$

and cld being the distance class to which belong $d_{i,j}$; $\delta_{c,cond,vcl,cld}$ and $\epsilon_{c,cond,vcl,cld}$ being the parameters of the dedicated crops transportation cost function (in €/km and €, respectively).

$$T_{i,j}^{EWood}\left(LBD_{w,i,j}^{EWood}\right) = \sum_{w,cond,vcl}\left(t_{w,cond,vcl,i,j}^{EWood} \cdot LBD_{c,cond,vcl,i,j}^{EWood}\right) \tag{39}$$

with :

$$t_{w,cond,vcl,i,j}^{EWood} = \vartheta_{c,cond,vcl}^{EWood} \cdot d_{i,j}^2 + \delta_{c,cond,vcl}^{EWood} \cdot d_{i,j} + \epsilon_{w,cond,vcl}^{EWood} \tag{40}$$

and $\vartheta^{EWood}_{c,cond,vcl}$, $\delta^{EWood}_{c,cond,vcl}$, and $\epsilon^{EWood}_{w,cond,vcl}$ being the parameters of the quadratic transportation cost function for wood (in €$/km^2$, €/km, an € respectively.

7.A Nomenclature

Name	Definition
Indices	
i, j	departure and arrival counties
c	crops, including dedicated crops
cld	distance class
$cond$	types of conditionning for the lignocellulosic biomass
r	crops rotations
s	soil types
vcl	vehicle types
w	woody biomass types

Table 13

Name	Definition	Unit
Variables		
$LBD_{i,j}^{ENERGY}$	amount of lignocellulosic biomass (energy crop, straw or wood) delivered to county j from county i	(tons)
$LBD_{c,i,j}^{ECrop}$	amount of energy crop delivered to county j from county i	(tons)
$LBD_{i,j}^{EStraw}$	amount of energy straw delivered to county j from county i	(tons)
$LBD_{w,i,j}^{EWood}$	amount of woody biomass of type w delivered to county j from county i	(tons)
$locus_j$	binary variable is equal to 1 if a bioenergy facility is located in county j and to 0 otherwise	
$S_{r,s,i}^{ROT}$	area of rotation r grown on soil s in county i	(ha)
$X_{c,s,i}^{CROPS}$	quantity of crop c (energy or non-energy crop) produced in county i on soil s	(tons)
X_i^{ENERGY}	total energy feedstock supply of county i	tons
X_i^{ECrop}	annual and perennial dedicated crops supply of county i	tons
X_i^{EStraw}	amount of straw devoted to energy use in county i	(tons)
X_i^{EWood}	amount of wood devoted to energy use	tons
X_i^{NEWood}	amount of wood devoted to non-energy use	tons
W_i^{WOOD}	wood volume of trees to be cut	m^3

Table 14

Name	Definition	Unit
Parameters		
α_i	Share of straw that can be exported from the county without harming its soil organic matter content	
$\gamma_{c,r}$	Share of crop c in crop rotation r	
$c_{c,s}^{prod}$	crop c production cost on soil s	€/ha
c_c^{cond}	energy crops conditionning cost	€/ton
c_{straw}^{cond}	straw conditionning cost	€/ton
$c_{w,cond}^{harv}$	harvest cost per type of woody biomass and conditionning	€/ton
$c_{w,cond}^{stump}$	stumpage per wood type and conditionning	€/m^3
$d_{i,j}$	distance between counties	km
D^{ENERGY}	exogenously given demand of a facility for lignocellulosic biomass	(MWh eq.)
lhv^{ENERGY}	energy content (lower heating value) of lignocellulosic biomass (energy crop, straw, or wood)	(MWh/ton)
lhv_c	energy content (lower heating value) of crop c	(MWh/ton)
lhv_{straw}	energy content (lower heating value) of straw	(MWh/ton)
lhv_w	energy content (lower heating value) of woody biomass	(MWh/ton)
p_c	crop price	€/ton
p^{MWh}	energy feedstock price / lignocellulosic biomass price	€/MWh
ρ	density of wood	$(tons/m^3)$
$t_{c,cond,vcl,i,j}$	energy crops transportation cost	€/ton
$t_{w,cond,vcl,i,j}^{EWood}$	wood transportation cost	€/ton
UAA_i	total utilised agricultural area available in county i	(ha)
$\overline{W_i^{WOOD}}$	maximum volume of wood that can be harvested annually in county i	m^3
$y_{c,s}$	Yield of crop c grown on soil s	(ton/ha)
$y_{c,i}^{straw}$	Yield of straw from cereal crops	ton/ha

Table 15

8 Appendix Case study

tab:Data sources Details on data sources and processing as well as data providers for the models' parameters are summarized in the following table (see table16).

Table 16 Details on data sources and processing.

Parameters	Comments	Sources
Agricultural data		
Aggregated Small Agricultural Regions	GIE Arvalis-ONIDOL aggregated the 27 SARs of the region (INSEE classification) into 8 groups and linked each county to one of these groups.	ECOBIOM project
Agricultural and fodder areas per county	Based on year 2005 farmers declaration for CAP subsidies. Aggregated at the county level for cash crop farms on the one hand and for bredding and dairy farms on the other hand.	ONIGC (French Inter-professional Office of Crop Farming) (purchased by Arvalis)
Permanent grassland areas	They were estimated for cash crop farms at the département level, based on SAA 2007 PG areas and the share of PG areas located in farm types 13 and 14 (enquête structure 2007, stru 005). We then assumed that these permanent grassland areas are uniformly distributed within the counties belonging to a given département.	SAA 2007,enquête structure 2007
Existing crops and crop rotations	Based on a survey of local experts by Arvalis. The three main rotation patterns in te regions were identified by local Arvalis experts.	Arvalis, regional extension officers (CRA), and Rural Economic Centers (CER), (ARVALIS, 2007)

Continued on next page

Table 16 continued from previous page

Parameters	Comments	Sources
Food crops yields, production costs and prices.	Yields and production costs are averages over a 10-year period (1997-2007). Food crops prices provided for years 1993 to 2007.	CERs (Centres d'Economie Rurale) of départements de l'Aube and Haute-Marne,(ARVALIS, 2007) .
Food crops price scenarios	The three price scenarios (mean, 1^st, and 9^th decile of the 1993-2007 prices were kindly computed and provided by C. Gouel (INRA).	
Dedicated crops yields and production costs	Based on first results from field trials	REGIX research project[9], (ARVALIS/ONIDOL, 2009a).
Poplar SRC data	The potential production areas for each of the 3 types of poplar SRC were obtained by overlaying soil, land use and county borders maps, following a methodology developped in the framework of the VALERBIO project	FCBA
Input use data	Information on the amount of nitrogen fertilizer, the number of pesticides and herbicides treatments, and fuel consumption, per crop and small agricultural region.	Arvalis, FCBA

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[9]REGIX was funded by the French National Research Agency (ANR, Agence Nationale de la Recherche) under the National Research Programme on Bioenergy (PNRB, Programme National de Recherche sur les Bioénergies) and coordinated by F. Labalette, GIE Arvalis-Onidol.

Table 16 continued from previous page

Parameters	Comments	Sources
Forest data		
Forest features	Forest stands maps and departemental statistics	IFN (French National Forest Survey)
	Stands' slopes	IGN
	Distance from plots to the nearest road	SERFOB (Service Régional de la FOrêt et du Bois)
Net annual harvestable wood volume per county	Computed by FCBA from IFN, IGN and SERFOB data, accounting for harvesting losses, wood volumes that are unharvestable due to technical logging difficulties or to the reluctance of small private owners.	FCBA
Harvesting costs, stumpage and wood prices	They were provided for Champagne-Ardenne by the French Association of Forest Cooperatives (Union des Coopératives Forestières de France, UCFF) and were harmonised with those from the French National Forestry Service (Office National des Forêts, ONF)	UCFF, ONF .

Continued on next page

Table 16 continued from previous page

Parameters	Comments	Sources
Transportation data		
Distance data	Kindly provided by M. Hilal	Distancier Intercommunal Route 500, INRA UMR 1041, CESAER, Dijon, France.
Transportation costs	Based on the CNR 2008 trinomial formula, adapted by FCBA for wood and by Arvalis for crops.	FCBA, Arvalis, CNR.

8.A Agricultural data

The composition of the various crop rotations included in the model as well as their compatibility with the various Small Agricultural Regions are provided in tables 17 to 20.

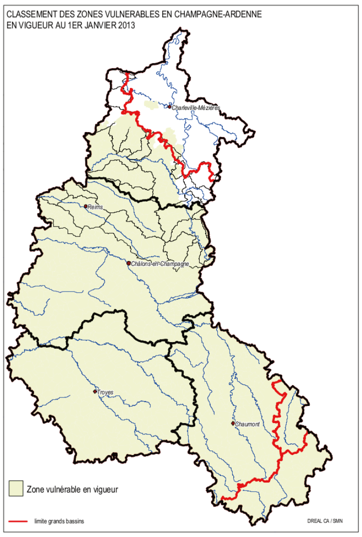


Fig. 18. Map of the Nitrates Directive "vulnerable zones" in 2013 for the Champagne-Ardenne region.

	ROT1	ROT2	ROT3	ROT4	ROT5	ROT10	ROT11	ROT12	ROT32
	rapeseed wheat barleyW	rapeseed wheat barleyW peaS wheat/gpc	rapeseed wheat barleyS	rapeseed wheat barleyS sugar beet wheat	maize wheat wheat/w sunflower wheat	maize wheat peaS wheat/gpc	rapeseed wheat wheat/w barleyW	rapeseed wheat wheat/w sugar beet wheat	maize wheat wheat/w rapeseed wheat
	ROT1	ROT2	ROT3	ROT4	ROT5	ROT10	ROT11	ROT12	ROT32
SAR1			1		1				1
SAR2	1	1	1		1	1	1		1
SAR3	1	1	1	1	1	1	1	1	1
SAR4	1	1	1	1	1	1	1	1	1
SAR5	1	1	1	1	1	1	1	1	1
SAR6	1	1	1		1	1	1		1
SAR7	1	1	1		1	1	1		1

Table 17
Food crop rotations and their compatibility with the Small Agricultural Regions (part1)

ROT6	ROT7	ROT8	ROT9	ROT34	ROT35	ROT36	ROT37
alfalfa1	alfalfa1	alfalfa1	horsebean pea	rapeseed	rapeseed	rapeseed	rapeseed
alfalfa2	alfalfa2	alfalfa2	wheat/gpc	wheat	wheat	wheat	wheat
alfalfa3	alfalfa3	alfalfa3	barleyW	wheat/w	wheat/w	barleyW	barleyW
wheat/gpc	wheat/gpc	wheat/gpc	rapeseed	sunflower	sunflower	peaS	peaS
wheat/w	wheat/w	barleyW	wheat	wheat	wheat	wheat/gpc	wheat/gpc
sunflower	sunflower	rapeseed	barleyS	potatoeS	potatoeF	potatoeF	potatoeS
wheat	wheat	wheat	peaW	wheat/gpc	wheat/gpc	wheat/gpc	wheat/gpc
barleyW	barleyW	barleyS					
potatoeF	potatoeS	maize					
wheat/gpc	wheat/gpc	wheat					

	ROT6	ROT7	ROT8	ROT9	ROT34	ROT35	ROT36	ROT37
SAR1								
SAR2				1				
SAR3	1	1	1	1	1	1	1	1
SAR4				1	1	1	1	1
SAR5	1	1	1	1	1	1	1	1
SAR6				1				
SAR7				1				

Table 18
Food crop rotations and their compatibility with the Small Agricultural Regions (part2)

ROT13	ROT14	ROT28	ROT29	ROT30	ROT31
sugar beet	sugar beet	sugar beet	sugar beet	sugar beet	sugar beet
barleyS	wheat	wheat	wheat	wheat	wheat
rapeseed	rapeseed	barleyS	barleyS	barleyS	barleyS
wheat	wheat	rapeseed	rapeseed	rapeseed	rapeseed
barleyW	barleyW	wheat	wheat	wheat	wheat
alfalfa1	alfalfa1	barleyW	barleyW	sugar beet	sugar beet
alfalfa2	alfalfa2	potatoeF	potatoeS	wheat	wheat
alfalfa3	alfalfa3	wheat/gpc	wheat/gpc	barleyW	barleyW
wheat/gpc	wheat/gpc			potatoeF	potatoeS
barleyS	barleyS			wheat/gpc	wheat/gpc
potatoeF	potatoeS				
wheat/gpc	wheat/gpc				

	ROT13	ROT14	ROT28	ROT29	ROT30	ROT31
SAR1						
SAR2						
SAR3	1	1	1	1	1	1
SAR4			1	1	1	1
SAR5	1	1	1	1	1	1
SAR6						
SAR7						

Table 19
Food crop rotations and their compatibility with the Small Agricultural Regions (part3)

	ROT16	ROT17	ROT18	ROT19	ROT20	ROT21	ROT22	ROT23	ROT24
	miscanthus	switchgrass	rapeseed wheat triticaleWP	rapeseed wheat triticaleWP sugar beet wheat	rapeseed wheat triticaleWP peaS wheat/gpc	alfalfa1 alfalfa2 alfalfa3 wheat/gpc barleyW rapeseed wheat triticaleWP maize wheat	sorghumF wheat peaS wheat/gpc	sorghumF wheat wheat/w sunflower wheat	alfalfa1 alfalfa2 alfalfa3 wheat/gpc barleyW rapeseed wheat barleyS sorghumF wheat
	ROT16	ROT17	ROT18	ROT19	ROT20	ROT21	ROT22	ROT23	ROT24
SAR1	1	1	1		1				
SAR2	1	1	1		1		1	1	
SAR3	1	1	1	1	1	1	1	1	1
SAR4	1	1	1	1	1		1	1	
SAR5	1	1	1	1	1	1	1	1	1
SAR6	1	1	1		1		1	1	
SAR7	1	1	1		1		1	1	

Table 20
Energy crop rotations and their compatibility with the Small Agricultural Regions.

8.B Forest data

Here we provide examples of harvesting costs and stumpage.

		Very easy	Easy	Difficult	Very difficult
Big	Non-barked logs	13.3	16.7	18.9	22.2
	Long-barked logs	17	20	20	23
	Short-barked logs	19	22	23	26
	Wood chips	24	28	28	32
Medium	Long-barked logs	17	20	20	23
	Short-barked logs	19	22	23	26
	Wood chips	24	28	28	32
Small	Bundles	20		23	
	Wood chips	30	34	40	44

Table 21
Example of wood harvesting costs for softwood from old trees, depending on wood diameter, wood conditioning, and logging difficulty level (in €/ fresh ton).

		Non-barked logs	Long-barked logs	Short-barked logs	Bundles	Wood chips
Softwood	Big	52.222	15	17.273		11
	Medium		15	17.273		9
	Small				3	3
Poplar	Big	33	9.5			11
	Medium		9.5			9
	Small				3	3
Hardwood	Big	49.412	15			11
	Medium		15			9
	Small				3	3

Table 22
Stumpage depending on the species, wood diameter, and conditioning (in €/ fresh ton).

			$\delta_{c,cond,vcl,cld}$						$\epsilon_{c,cond,vcl,cld}$
Crop	Conditionning	Vehicle	cld0-25	cld25-50	cld50-100	cld100-150	cld150-200	cld200+	cld0
Straw	bale	cr5	0.153	0.104	0.087	0.081	0.087	0.076	0.076
triticaleWP	bale	cr5	0.153	0.104	0.087	0.081	0.087	0.076	0.076
miscanthus	bale	cr5	0.168	0.114	0.095	0.089	0.095	0.083	0.084
switchgrass	bale	cr5	0.179	0.122	0.102	0.095	0.102	0.089	0.090
miscanthus	silage	srb	0.273	0.187	0.157	0.147	0.157	0.137	0.137
triticaleWP	silage	srb	0.294	0.201	0.169	0.158	0.169	0.148	0.147
switchgrass	silage	srb	0.336	0.230	0.193	0.180	0.193	0.169	0.168
sorghumF	silage	srb	0.392	0.268	0.225	0.210	0.225	0.197	0.196
triticaleWP	silage	multib	0.306	0.208	0.174	0.162	0.174	0.152	0.153
miscanthus	silage	multib	0.312	0.212	0.177	0.165	0.177	0.155	0.156
switchgrass	silage	multib	0.383	0.260	0.218	0.203	0.218	0.190	0.191
sorghumF	silage	multib	0.515	0.351	0.293	0.274	0.293	0.256	0.258

Table 23
Coefficients of the transportation costs linear function for each distance interval (in €/ton/km), depending on the crop, its conditionning and the type of vehicle that is used (cr5 = camion remorque 5 essieux; srb = semi remorque avec benne; multib= multibenne). Source : Arvalis, based on the French National Road Center trinomial formula.

8.C Transportation costs

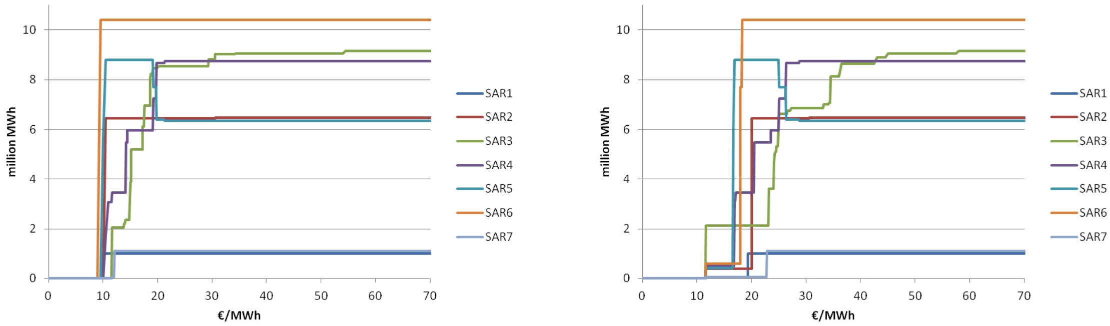
Agricultural biomass transportation costs, in form of piecewise linear functions per distance interval.

Woody biomass transportation costs, in form of quadratic functions of the distance .

Conditioning	Vehicle	$\vartheta^{EWood}_{c,cond,vcl}$	$\delta^{EWood}_{c,cond,vcl}$	$\epsilon^{EWood}_{w,cond,vcl}$
Logs	sr5	-0.00004	0.0444	7.2317
Logs	cr6g	-0.00004	0.0484	7.4646
Logs	sr6g	-0.00004	0.0492	7.058
Bundles	sr5	-0.00005	0.0555	9.0396
Bundles	sr6g	-0.00005	0.0636	9.1165
Wood chips	fma	-0.00004	0.0477	8.6335
Wood chips	polyb	-0.00006	0.0663	10.376

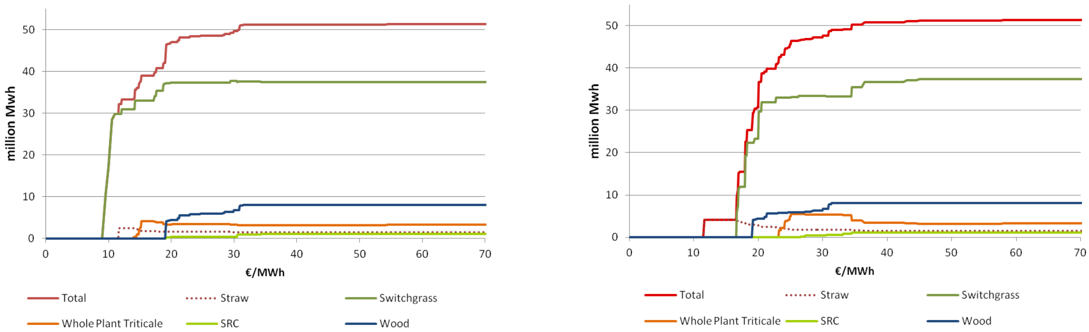
Table 24
Coefficients of the woody biomass transportation cost functions, depending on the biomass conditoning and type of vehicle(in €/fresh ton/km^2 , €/fresh ton/km, and €/fresh ton respectively). sr5 = semi remorque 5 essieux; cr6g = camion remorque 6 essieux avec grue; sr6g = semi remorque 6 essieux avec grue; fma = fond mouvant; polyb = poly-bennes. Source: FCBA, based on the French National Road Center trinomial formula.

9 Appendix Results



(a) (b)

Fig. 19. Detail of the amount of biomass supplied by each Small Agricultural Regions in the low and high prices context s(in million MWh).



(a) (b)

Fig. 20. Detail of the lignocellulosic biomass mix supplied in the low and high prices context (in millions MWh).