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Stochastic viability of second generation biofuel chains: Micro-economic spatial modeling in France*

Laure Bamière† Vincent Martinet† Christophe Gouel†‡

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Abstract

To better understand the production of biofuels derived from lignocellulosic feedstock, we investigate the interplay between the agricultural sector and a biofuel facility, at the local level. More specifically, we investigate the economic and technological viability of a bioenergy facility over time in an uncertain economic context using a stochastic viability approach. Two viability constraints are taken into consideration: the facility's demand for lignocellulosic feedstock has to be satisfied each year and the associated supply cost has to be lower than the facility's profitability threshold. We assess the viability probability of various strategies the facility can adopt to ensure that the agricultural sector meets its demand for biomass. These supplying strategies are determined at the initial time and define the constant share of total demand met by contracting out the demand to farmers who grow perennial crops. Any remaining demand is met by annual crops or wood. The demand constraints and agricultural price scenarios over the time horizon are introduced in an agricultural and forest biomass supply model, which in turns determines the supply cost per unit of energy and computes the viability probabilities of the supplying strategies. If a facility is to be viable over time, it is best for it to ensure that 100% of its demand is contracted out to farmers supplying perennial dedicated crops. This result is robust to the price context.

Keywords: Biofuel, biomass production, spatial economics, stochastic viability, Monte Carlo simulation.

JEL classification: Q12, Q16, Q42.

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1 Introduction

In a global context of efforts to reduce greenhouse gases emissions and to achieve energy independence, renewable energy sources (including biofuels and bioliquids) are presented as an alternative to fossil fuels. The European Union has set mandatory targets for 2020 for the share of energy from renewable sources in overall energy consumption in the Union, and for energy related to transport for each Member State, at 20% and 10%, respectively.[1] The European Commission has also emphasized the importance to produce renewable energy sources locally (e.g., to achieve supply security, employment and rural development opportunities) and in compliance with sustainability criteria. In this context, biomass is expected to play an important role : it is renewable, can be cultivated in all regions, converted into heat, electricity or biofuel, and stored in huge quantities. It is important to determine to what extent the agriculture and the forestry sectors could contribute to the production of bioenergy at both global and regional scales, in a sustainable way.

This issue has been addressed in several large scale studies that examine the potential global production (for a survey, see Berndes et al., 2003; EEA, 2006; Ericsson and Nilsson, 2006), which generally do not consider the economic conditions required for this production. Determining these conditions requires detailed modeling of the supply side, such as that in Rozakis and Sourie (2005) which examines the supply of first generation biofuels in France using a detailed micro-economic model of the agriculture sector to determine the profitability of the biofuel chain in an uncertain economic context.

The first generation of biofuels, however, is subject to sustainability concerns (Scarlat and Dallemand, 2011) since it competes with food production, potentially leading to increases in food prices (Zilberman et al., 2013), and appears less promising in relation to its environmental benefits as initially envisaged (Searchinger et al., 2008). Lignocellulosic biomass generally has higher energy content and yield for lower input levels; thus, the second generation of biofuels (based on cellulosic and lignocellulosic biomass, which includes agricultural and woody biomass) is advocated as being more compatible with the objectives of sustainable agricultural development.

However, there are problems related to this second generation of biofuels : the emergence of a lignocellulosic biofuels supply chain may prove difficult. Babcock et al. (2011) examine the market conditions for the emergence of a competitive cellulosic biofuel sector and show that sector competitiveness depends on both the institutional context (subsidies) and the competition with the traditional ethanol chain. They emphasize that the feedstock price is a key driver of the production cost of second generation biofuels, this price being determined locally because biomass transportation costs are high with respect to the value of the biomass and there is no existing market for cellulosic biofuel feedstock. However, their study does not consider the local feedstock supply, while forecasts on the contribution of biomass to future global energy supply vary widely with assumptions about land availability and yield levels (Berndes et al., 2003), and delivery costs are an important factor of profitability (Graham et al., 2000). Hellmann and Verburg (2011) use an aggregate top-down approach to assess European production possibilities. However, assessing the

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[1] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

profitability of production facilities requires accounting for the local context, along with uncertainty about the prices of agricultural commodities and, thus, about the opportunity cost of local cellulosic feedstock.

Ballarin et al. (2011) adopt a weighted goal programming model to assess the trade-offs between farmers' incomes and potential bioenergy production at the regional level, accounting for the local environmental and agronomic context, but without explicitly considering either the production facilities or the uncertainty in agricultural commodity prices, which would influence the actual production of bioenergy. Kocoloski et al. (2011) employ a mixed integer programming model to define the optimal location of cellulosic ethanol refineries at the U.S. level. Focusing on transportation costs, they show that ethanol production costs vary with the local availability of biomass, which emphasizes the role of the location of cellulosic ethanol facilities on their profitability. Their study accounts for the response of biomass supply to the feedstock price and competition over land-use with other commodities, but does not model explicitly the local price formation for cellulosic biofuel feedstock or the influence of price fluctuations in other commodities on supply costs and quantities. Methods and applications are thus missing to assess the local conditions for regional lignocellulosic bioenergy chains to emerge and, in particular, to examine the viability of bioenergy facilities in terms of biomass supply and supply cost.

In this paper, we examine the economic and technological viability of a bioenergy facility in an uncertain economic context, in terms of both the capacity to supply the facility with biomass of a quality consistent with the production under consideration, and in terms of associated supply costs. We apply a stochastic viability approach (De Lara and Martinet, 2009; Doyen and De Lara, 2010). In dynamic systems under uncertainty, this approach ranks management strategies with respect to the probability that they generate a trajectory of the system that respects a set of constraints over time. We consider a lignocellulosic bioenergy production facility that needs to define a supplying strategy for its input biomass. The facility has two viability constraints. On the one hand, it needs sufficient annual quantity of biomass to sustain energy production. On the other hand, the associated supply cost has to be lower than a threshold representing the facility's profitability price. Since this profitability threshold may depend on the type of facility, we provide a sensitivity analysis of this constraint level. We assess the viability probability of various supplying strategies based on the proportion of contracted perennial crops, i.e., the probability with which these strategies make it possible to respect the constraints over time in a stochastic context for agricultural commodity prices.

To describe the local agricultural context, we use a spatially explicit regional supply model for agricultural and forest lignocellulosic biomass. This model gives the response of production to fluctuating market prices as well as the composition, origin, and cost of the supplied biomass. The model is not specific to a given technology. The methodology is general, but for illustrative purposes it is applied to the enzymatic hydrolysis and fermentation technology (to produce bioethanol from lignocellulosic biomass), using data for the Champagne-Ardenne region (France) over a fifteen years time period.

The paper is structured as follows. Section 2 describes the methodology and modeling approach. Section 3 describes the case-study and introduces the scenarios. Section 4 analyzes the numerical results and Section 5 provides a discussion and conclusions.

2 Methodology

The methodology is aimed at defining i) the viability probability of various supplying strategies for the biomass supply of lignocellulosic bioenergy chains, ii) the associated supplying cost, and iii) the spatial origin and type of biomass.

2.1 The stochastic viability approach

Adopting the viewpoint of a lignocellulosic bioenergy facility, we look for the supplying strategies that maximize the technological and economic viability of the facility, under price uncertainty. For this purpose, we use the stochastic viability approach (De Lara and Martinet, 2009; Doyen and De Lara, 2010). The viability approach consists in examining the consistency of a dynamic system with a set of so-called viability constraints, i.e., in determining if it is possible to satisfy the constraints over time, starting from a given initial state of the system (Aubin, 1991). In the stochastic framework, the probability of respecting these constraints over time is used to rank strategies.

We consider two viability constraints: i) the facility's demand for lignocellulosic feedstock D (in primary energy equivalent of adequate biomass) has to be satisfied each year; and ii) the associated supply cost (mean cost per unit of input energy) has to be lower than a threshold $\bar{P}$ representing the profitability of the process.

The facility's supplying strategies consist in contracting a share of the feedstock demand to perennial dedicated crops, Q_0^{pc}, at the initial time $t = 0$ for a contractual price P_0^{pc}. This quantity is then supplied at this price each year over the planning horizon. The remaining demand is then met by annual dedicated crops or wood, Q_t^{ac}, at a price P_t^{ac} that depends on the market conditions that year.

The two viability constraints read as

$$Q_t^{ac} + Q_0^{pc} \geq D, \tag{1}$$

and

$$\frac{P_t^{ac} Q_t^{ac} + Q_0^{pc} Q_0^{pc}}{Q_t^{ac} + Q_0^{pc}} \leq \bar{P}. \tag{2}$$

The facility is said to be technologically and economically viable when these constraints are satisfied at all periods over the planning horizon. We rank the supplying strategies with respect to their probability to satisfy both constraints at all time periods, over the planning horizon. We assume that the supplying strategies vary according to the share of total demand met by contracting out the demand to farmers who are growing perennial crops. Here, uncertainty is related to the supply price of annual biomass, P_t^{ac}, which depends on exogenous shocks on agricultural prices (global price context) and on the supplying strategy (local biomass price formation).

The profitability threshold (maximal cost of supply) of a given plant depends on its technology and the output price. As our model is not restricted to a particular type of cellulosic bioenergy facility, we treat this maximal cost $\bar{P}$ as a parameter and perform a sensitivity analysis on its value.[2]

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[2] Moreover, the actual profitability threshold of a given facility is a private and strategic information that is not easy to assess.

From a technical point of view, this viability probability can be approximated by a frequency using Monte-Carlo simulations, by simulating a large number of agricultural price scenarios (one such being a sequences of prices for all commodities over the planning horizon) and examining the success frequency of each strategy across these scenarios. This approach requires us to model the response of regional agricultural production to prices. Price scenarios are generated using a stochastic agricultural price model. The demand constraints, strategies and agricultural prices scenarios are introduced in an agricultural and forest biomass supply model, which, in turn, determines the mean supply cost per unit of energy and computes the viability probabilities of the various supplying strategies.

2.2 The modeling framework

We aim at modeling the dynamic land-use of an agricultural region to determine the quantities produced in response to local market incentives for biomass supply and global market incentives for other commodities. The model must in particular define the local biomass price.

We consider an agricultural region where land use maximizes farmers' gross margins. Farmers are price takers for non-energy commodity prices, in the sense that local production does not affect the price of these commodities. At the beginning of year t, anticipated prices for these agricultural outputs are formulated with respect to past observed agricultural commodity prices. At the same time, the region faces a demand for biomass from a bioenergy production facility. This demand, in primary energy equivalent, is given and is supposed non-flexible. The local market for lignocellulosic biomass sets a price for biomass supply, and land allocation and commodity production are then defined to maximize the region's total gross margin.

For simplicity, to determine the price of local biomass we assume the following. A unit of biomass will be produced and delivered to the plant if the local price is higher than the foregone revenue from the best agricultural production alternative plus biomass production and delivery costs. Thus, the local market is cleared at a price that equals the opportunity cost of the last unit of biomass delivered to the bioenergy production plant.

2.2.1 Modeling the global economic context: Stochastic price scenarios

Uncertainty in our application is related to stochastic commodity prices. A scenario is a sequence of prices for all commodities (except biomass traded on the regional market) over the 15-year planning horizon.

We assume that market prices for commodities can be represented as a VAR process.[3] The price level equation is

$$p_t = A + Bt + Cp_{t-1} + u_t, \tag{3}$$

where p_t is the vector of the logarithm of prices; A and B are the coefficient vectors of exogenous variables: a constant and a trend; C is the coefficient matrix; u_t is the error term, with $\mathrm{E}(u_t) = 0$ and $\mathrm{E}(u_t u_t') = \Sigma_u$.

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[3] A VAR model makes it possible to represent the serial correlation (Deaton and Laroque, 1992) and the co-movement of commodity prices (Pindyck and Rotemberg, 1990; Ai et al., 2006). We follow Beck (2001) by introducing a time trend that accounts for the effect of productivity change or demand change on prices.

The time series available for local prices are too short to estimate a VAR on annual prices. Since primary commodity markets are well integrated internationally, in our estimation we use the international commodity price indexes provided by Grilli and Yang (1988) and updated by Pfaffenzeller et al. (2007). Prices are annual and extend from 1900 to 2003. They are deflated by the United Nations Manufactures Unit Value index. We use price information on corn, palm oil, wheat, and timber. We consider them as reference prices for all the other commodities.

The estimation results are presented in Table 1. They show that prices have a positive first order correlation, a behavior that can be related to the effect of storage, which tends to smooth shocks over several periods (Deaton and Laroque, 1992). It implies that a period of low (high) prices is most likely to be followed by low (high) prices. Lagged effects of one commodity over another are limited. Nonetheless, prices move together because of common contemporaneous shocks, as shown by the covariance matrix of residuals.

Table 1

VAR estimates of commodity prices dynamics

	Wheat	Corn	Palm oil	Timber
time	-0.003^{*}	-0.005^{**}	-0.002	0.003^{**}
Wheat(−1)	0.566^{***}	-0.061	0.018	-0.011
Corn(−1)	0.108	0.560^{***}	0.285^{**}	0.065
Palm oil(−1)	0.051	0.153	0.560^{***}	0.009
Timber(−1)	0.017	0.077	0.022	0.736^{***}
R^2	0.828	0.803	0.818	0.877
Covariance matrix of residuals:				
Wheat	0.024			
Corn	0.019	0.039		
Palm oil	0.006	0.016	0.042	
Timber	0.005	0.007	0.012	0.016

Notes: The constant is omitted in the results. *, ** and *** denote significance at the 10%, 5% and 1% level.

We use this estimation to simulate potential price trajectories, by drawing shocks from a centered multivariate normal distribution of covariance matrix Σ_u. We remove the time trend and rescale the equations by multiplying them by the average of 15-year Champagne-Ardennes prices and dividing them by their estimated price means.

In addition to the simulated prices, we calculate the corresponding conditional expectations, which are used to endow farmers with rational expectations of next period prices. We consider that, at the regional level, farmers are price taker for marketed commodities, i.e., the local production does not affect global prices, and take their land-use decisions as based on expected prices depending on past observations. This results in a sequence of locally anticipated price series, which represent uncertainty scenarios for the bioenergy facility.

As the production of perennial cellulosic crops requires a long-run commitment from farmers, it depends on the opportunity cost of alternative crops at the initial year. We consider three different price contexts in which the initial agricultural prices are set to different values. In the benchmark scenario the initial prices are equal to the mean prices for 1993–2007. In the "low prices" scenario agricultural prices start from values equal to the 1st decile of the 1993–2007 prices. Correspondingly, the "high prices" scenario corresponds to the 9th decile of the 1993–2007 prices.

An example of a simulated price path starting from a high price situation is illustrated in Fig. 1. In addition to the simulated prices (plain line), price expectations are represented in two variants: next-year expected price (dashed-line), $E_{t-1}(P_t)$, on which farmers base their land allocation for annual crops, and t-year ahead expected price (dotted-line), $E_0(P_t)$, which is the relevant price for the farmers' supply strategy. Notice that this latter price converges to its long-run average, what illustrates the mean-reversal aspect of the price dynamics.

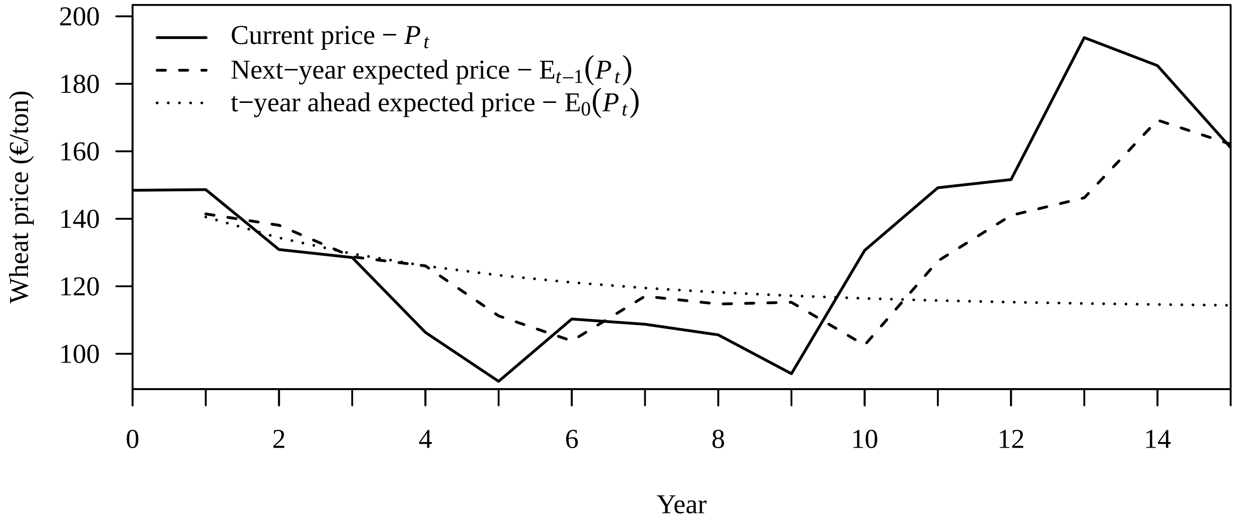

Fig. 1. Example of a simulated "high price" scenario

2.2.2 Modeling the regional biomass supply and associated costs

To assess the supplying costs of the bioenergy facility and the spatial origin and type of biomass, we use a spatially explicit regional supply model for agricultural and forest lignocellulosic biomass. It accounts for two spatial levels: county and region.

The county is the smallest administrative (sub)level for which data are available. In our model, the county is the spatial level at which production decisions occur, taking account of technical and economic constraints. Each county is characterized by its soil composition, altitude, and the slope of forest stands. It is the elementary unit for locating biomass departure and delivery points. We denote the number of counties by A and the number of agricultural commodities by I. Decision variables at county level are the area devoted to each commodity for field crops[4] and the harvested wood quantities per category for forest.[5] The area devoted to the production of commodity i in county a is denoted by $X_{i,a}$. For simplicity, we denote the land use of county a by the compact expression X_a. Production is characterized by the biomass and crop yields and production costs, as well as available wood quantities per category and related stumpage and harvesting costs. The production and production cost functions of commodity i in county a depend on the land use X_a in that county and are denoted by $Q_{i,a}(X_a)$ and $C_{i,a}(X_a)$.

The region is the relevant level when it comes to drawing the boundaries of the biomass supply area and studying the competition for resources that arises when a bioenergy facility is being set up. It is the level at which distances and transportation costs from counties to the bioenergy facility are accounted for. The type, quantity, and conditioning of biomass supplied to the bioenergy facility are determined optimally at the regional level.[6] At initial time $t = 0$, the facility contracts out dedicated perennial crops at the contractual price P_0^{pc} to meet a part γ of its demand D according to the supplying strategy.[7] The corresponding areas in perennial crops are then removed from production in each county for the rest of the planning horizon. The remaining area of county a is denoted by L_a. The share of demand that is not supplied by contracted perennial crops has to be supplied by annual dedicated crops or wood. The annual demand for biomass is expressed in primary energy equivalent and is denoted by $(1-\gamma)D$. It depends on the considered supplying strategy. The quantity of commodity i supplied to the bioenergy facility by county a is denoted by $S_{i,a}$. Its lower heating value is denoted by ρ_i. The associated transportation cost function is denoted by $T_{i,a}(S_{i,a})$. We consider that farmers take their land-use decisions using expected prices, as described above. The expected price for commodity i is denoted by P_i. The local market for biomass is defined so as to supply the demand $(1-\gamma)D$ to the facility at the lowest possible cost.

We use a mathematical programming model to maximize the region's agricultural and forestry income, considering the various potential uses of biomass (food, energy, industry or timber). Here, we present a stylized version of the model, treating all commodities the same way.[8] The optimization problem is as follows:[9]

$$\max_{\{X_{i,a}\geq 0, S_{i,a}\geq 0\}} \sum_{a=1}^{A}\sum_{i=1}^{I}\left\{P_i\left[Q_{i,a}\left(X_a\right)-S_{i,a}\right]-C_{i,a}\left(X_a\right)-T_{i,a}\left(S_{i,a}\right)\right\}, \tag{4}$$

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[4] Formally, the model considers crop rotations, which means that there are (agronomic) constraints linking the areas devoted to each commodity.

[5] In what follows, for the sake of clarity, we omit the time subscript.

[6] The biomass delivered to the plant is not always to be used as it is and may require a pre-treatment (e.g., drying or chipping), inducing an extra cost that could change the optimal biomass supply. This could be easily included in our model if the technology of the facility is specified.

[7] See below how this price and the supplying conditions (type, quantity, and origin of the biomass) are determined.

[8] Forest areas are actually independent from agricultural areas and wood products are described with quantities rather than with surfaces in the model.

[9] This model is a linear programming model as the location of the biomass processing plant is given. It is written in GAMS and solved with the CPLEX solver.

$$\text{subject to} \qquad L_a - \sum_{i=1}^{I} X_{i,a} \geq 0, \quad \forall a \tag{5}$$

$$\sum_{a=1}^{A} \sum_{i=1}^{I} S_{i,a}\rho_i - (1-\gamma)D \geq 0, \tag{6}$$

$$Q_{i,a}(X_a) - S_{i,a} \geq 0, \quad \forall i,a \tag{7}$$

Constraints (5) represent the land availability in all counties. Constraint (6) represents the market condition to meet the technological viability constraint (biomass demand). The dual value of the demand constraint (6) is the opportunity cost of the last energy unit delivered to the facility, i.e., the foregone revenue of the best production alternative plus biomass production and shipping costs. It provides the purchase price of annual feedstock, P_t^{ac}.

We use this model to determine the optimal land use and assess the opportunity cost of biomass.[10] The model is used recursively to determine the intertemporal optimal land use, the quality and origin of the annual biomass delivered to the lignocellulosic bioenergy facility, and the related opportunity cost, P_t^{ac}. For each simulation scenario, the total biomass supply cost is computed each year following equation (2) and is compared to the economic profitability threshold of the facility.

3 Case study

As a case study, we consider a second generation ethanol production facility setting-up in the French Champagne-Ardenne region. This agricultural and forested region includes 146 counties with both agricultural and forestry activities. Different types of lignocellulosic crops can be grown there and R&D activities in the field of second generation biofuels are established in the area. The facility uses 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 the case of a project under study in the region. Considering the current process energy efficiency of 0.39 (Schmidt et al., 2010) and a 7000 hours/year workload hypothesis, this implies a biomass input of 389.8 MW/year. The optimal location of the facility was determined in Bamière (2013).

3.1 Model data and assumptions

We assume here that: i) agricultural and forest areas are independent, i.e., deforestation and afforestation are not allowed; ii) short rotation coppices (SRC) can only be grown on agricultural areas; iii) all biomass is available at the county seat. We account only for the agricultural area of crop farms.[11]

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[10] To determine the nature, quantity and origin of contracted biomass, we ran the same model with an additional constraint on dedicated perennial crops, so that a quantity γD is supplied by these crops.

[11] Types of Farming 13 and 14 in accordance with the Farm Accountancy Data Network classification.

Soil and agricultural data. We account for 7 soil types. Based on their agropedoclimatic characteristics, counties can grow 13 conventional crops and 5 dedicated crops: miscanthus, switchgrass, whole-plant triticale, fiber sorghum, and poplar SRC. Crops are combined into 33 crop rotations, among which 9 contain dedicated crops, plus poplar SRC. Crop rotations allow accounting for the preceding and following crop effects on yields, input consumptions (e.g. nitrogen balance) and environmental impacts. Moreover, considering rotations facilitates comparison of crop rotations (composed of annual crops) to perennial crops such as miscanthus, switchgrass, and SRC. We assume that farmers will substitute perennial crops for existing crop rotations, and that annual dedicated crops will likely substitute to equivalent crops in crop rotations (whole-plant triticale substitutes to barley, and fiber sorghum to maize). For conventional crops, regional data were collected to compute average yields and production costs over the period 1997–2007.[12] The yields of dedicated crops are estimated based on the first results from field trials.[13] The associated production costs for perennial crops are used to compute an equivalent annual cost (with a 5% discount rate) over the whole rotation duration. Dedicated crops can be conditioned into silage or high density bales.

Forest data. The annual wood volume available to harvesting per county depends on the characteristics of the existing forests (area, location, ownership, species, age of trees and slope of plots). It was computed by the French Technological Institute for Forest, Cellulosis, and Building lumber (FCBA) based on three main data sources.[14] For the Champagne-Ardenne region there are 60 harvested wood categories and 5 types of conditioning (non-barked logs, long barked logs, short barked logs, bundles, and woodchips). Harvesting costs (including felling cost, tree processing, and hauling costs), stumpage (the price paid by an operator to the land owner to harvest the standing timber on his land) as well as wood prices for the region were provided by the French Association of Forest Cooperatives and harmonized with the French National Forestry Service data.

Transportation data. We use the distances that minimize transportation time.[15] Transportation costs per metric ton and kilometer are calculated using the trinomial formula from the "French National Road Center" (Centre National Routier, CNR), based on kilometric costs, hourly rates, and fixed costs as well as the type of vehicle used.[16]

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[12] Arvalis, cropping surveys made by Rural Economics Centres (Centres d'Economie Rurale, CER) from Département de l'Aube and Département de la Haute Marne, and expert knowledge.

[13] From the REGIX project, financed by the French National Research Agency under the National Research Programme on Bioenergy.

[14] The French National Forest Survey, the French National Geographical Institute, and the Regional Wood and Forest Department.

[15] Distancier intercommunal Route 500, INRA UMR 1041 CESAER, Dijon.

[16] Wood transportation costs were provided by the FCBA, in the form of quadratic transportation cost functions. Crop transportation costs data were gathered and computed per distance interval by ARVALIS based on CNR 2008 data. The choice of the vehicle depends on the type of biomass, its conditioning, the slope of the forest stand, and the distance to cover. We account for 8 types of vehicle, 5 for wood and 3 for crops.

3.2 Validation

To validate our model, we compare 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 2006 agricultural prices in the region, subject to constraints on the sugar beet, starch potato, and food potato areas at *département* level. We compare our simulated land use to data on farms growing cereal, oilseed and protein crops, provided by the French agricultural bureau of statistics (Statistique Agricole Annuelle and Enquête structure 2007) at *département* level, which is the smallest administrative level for which data are available. Results show that they are quite similar. For more detail on validation results, see Bamière (2013).

3.3 Baseline

We run the model for the three initial price contexts with zero demand for lignocellulosic feedstock, which is currently the case, to obtain a baseline for agricultural production and wood harvest and use if there is no bioenergy facility operational in the region. Results are provided in Table 2 and Table 3. Table 2 shows that when agricultural prices are higher, the share of wheat, maize, and sunflowers tends to increase at the expense of barley, alfalfa, and rapeseed. Table 3 shows that the total amount of wood harvested remains quite similar regardless of the level of wood prices. However, when wood prices increase, the type of conditioning changes and logs are preferred to woodchips.

Table 2

Crop area and production for the baseline depending on the initial agricultural price level

	Low		Benchmark		High	
	Area ($10\ km^2$)	Production (10^3 t)	Area ($10\ km^2$)	Production (10^3 t)	Area ($10\ km^2$)	Production (10^3 t)
Wheat	437	3,482	501	3,993	556	4,442
Spring barley	115	770	75	502	60	404
Winter barley	31	242	23	183	15	118
Rapeseed	109	396	95	347	83	300
Sunflower	34	102	61	169	113	327
Maize	93	710	108	879	121	1,002
Peas	39	156	36	174	0	0
Sugar beet	89	7,973	89	8,009	89	8,009
Potatoes	11	512	11	512	11	512
Starch Potatoes	5	206	5	206	4	186
Alfalfa	92	1,167	50	668	0	0

Table 3

Wood production for the baseline depending on the initial agricultural price level (10^3 metric tons)

Price level	Wood	Non-barked logs	Long barked logs	Short barked logs	Bundles	Woodchips	Total
Low	Softwood	548	0	396	61	1,352	2,358
	Poplar	104	33	0	4	0	141
	Hardwood	154	147	0	17	181	498
Benchmark	Softwood	548	0	1,111	61	645	2,366
	Poplar	104	33	0	4	0	141
	Hardwood	202	161	0	17	140	521
High	Softwood	548	0	1,676	61	81	2,366
	Poplar	104	33	0	4	0	141
	Hardwood	202	252	0	17	54	525

3.4 Simulations

Price scenarios. The VAR model described above is used to simulate 500 anticipated price series (i.e., 500 price scenarios) over 15 years. Prices at $t = 0$ in the benchmark context are Champagne-Ardenne mean prices for the 1993–2007 period (and the 1st and 9th deciles for the low and high price contexts). Given that markets for vegetable oils are known to be strongly interrelated (In and Inder, 1997), we use price information on palm oil to substitute for the oilseeds represented in the model: rapeseed and sunflower. There is also a strong relationship between wheat and barley (Dawson et al., 2006). We assume that barley, peas and horse bean prices follow wheat price variations. The prices of the other crops (e.g., sugar beet, potatoes) are assumed to be constant over time. The different categories of wood are assumed to follow the price dynamics of timber estimated in the VAR model.

Contractual prices as well as the type and area of contracted perennial crops are fixed at $t = 0$, whereas model simulations to assess viability start at $t = 3$ when the facility is up and running and when perennial dedicated crops start to be productive.

Supplying strategies. We compare 6 supplying strategies, consisting in contracting either 0%, 20%, 40%, 60%, 80% or 100% of the lignocellulosic feedstock demand (in primary energy equivalent) with perennial crops, i.e., miscanthus, switchgrass or poplar SRC in our study. Remaining demand has to be satisfied each year with wood or annual dedicated crops, i.e., whole-plant triticale and fiber sorghum in our study. These strategies are denoted respectively sb0, sb20, sb40, sb60, sb80, and sb100.

4 Results

The results are presented as follows. We first describe the type, origin, and price of the biomass supplied in the various supplying strategies considered. Second, we compare strategies according to their viability probability, and show that strategies based on higher contractual shares are more viable. Last, we provide a sensitivity analysis of these results with respect to the price context of the contracting year, exhibiting the robustness of our analysis.

4.1 Agricultural land use and lignocellulosic biomass production

When a demand for lignocellulosic biomass appears, switchgrass silage is the perennial biomass contracted by and delivered to the bioenergy facility. The contracted perennial biomass (switchgrass) is grown in the county where the facility is located, on the region's most fertile and profitable soil categories (in terms of agricultural yields and gross margins). Its total area ranges from 6,716 ha to 33,582 ha depending on the supplying strategy (the larger the part of contracted biomass, the larger the area of switchgrass).[17] Its opportunity cost (i.e., P_0^{pc}) ranges from 12.95 €/MWh to 13.33 €/MWh (see Table 4), i.e., from 60.1 €/t to 61.9 €/t dry matter or from 1052.2 €/ha to 1083.1 €/ha. The farm gate opportunity cost we obtain is consistent with what is currently offered to farmers for perennial crops in France. The fact that switchgrass is more profitable than miscanthus for farmers is also consistent with existing economic analysis at farm level in France (Bocquého and Jacquet, 2010).

Table 4

Supplied biomass prices for the different supplying strategies at $t = 0$ (€/MWh)

	sb0	sb20	sb40	sb60	sb80	sb100
Shadow price of the contracted biomass, P_0^{pc}	–	12.98	12.95	13.33	13.28	13.07
Shadow price of the annual biomass for the base year, P_0^{ac}	19.74	19.44	19.27	18.99	18.58	–

For supplying strategies that are not based exclusively on contracted perennial crops (i.e., sb0 to sb80), the residual, non-contracted demand is filled by annual dedicated crops. Table 5 shows the type and quantity (metric tons) of annual biomass supplied to the bioenergy facility on average over the 500 price scenarios. The larger the contractual biomass supply, the smaller the annual supply. Actual annual biomass supply in each scenario depends on the absolute and relative levels of agricultural prices. It is composed mainly of whole plant triticale and to a lesser extent of fiber sorghum and wood. It shows great variability over the price scenarios (standard deviation is often higher than the mean), which implies that the facility's transformation process has to be flexible. If the facility prefers to limit the supply to a few biomass sources, it will therefore be more expensive.[18]

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[17] At the region level, for the supplying strategy sb100, the demand for swithgrass leads to a decrease of alfalfa and peas areas by 14 to 12%, of wheat and maize areas by 4% and to a rise of spring barley areas by 6%.

[18] Our model can easily be modified to account for constraints on the type and quality of biomass delivered to the facility.

Table 5

Type of biomass delivered to the facility in the benchmark case (mean and standard deviation over the 500 price scenarios, metric tons)

	sb0		sb20		sb40	
	Mean	SD	Mean	SD	Mean	SD
Switchgrass	0	–	117,537	–	235,073	–
Whole-plant triticale	570,534	74,322	458,130	59,502	345,549	44,938
Fiber sorghum	61,533	60,901	48,249	49,418	34,955	37,568
Softwood logs	1,272	4,056	734	2,569	360	686
Softwood bundles	53	152	27	83	11	7
Softwood woodchips	31,642	53,076	24,599	43118	17,618	22,501
Hardwood woodchips	416	1,005	247	616	130	151
	sb60		sb80		sb100	
Switchgrass	352,610	–	470,146	–	587,683	–
Whole-plant triticale	231,177	30,391	112,847	16,894	–	–
Fiber sorghum	22,988	25,329	14,502	14,796	–	–
Softwood logs	133	686	25	153	–	–
Softwood bundles	3	7	1	2	–	–
Softwood woodchips	11,133	22,501	5,214	11,170	–	–
Hardwood woodchips	64	151	27	57	–	–

For example, at the initial time, demand is satisfied by whole-plant triticale. This annual dedicated crop substitutes to spring barley and wheat in the rotations usually grown in the three most fertile and profitable soil categories in the region.[19] Depending on the supplying strategy, the opportunity cost of whole-plant triticale silage ranges from 18.58 €/MWh (for sb80, where only 20% of biomass demand is filled by annual crops) to 19.74 €/MWh (for sb0, where total demand is filled by annual crops). This gives the opportunity cost of the last unit of energy delivered to the facility (i.e., P_0^{ac}).

Note that in this benchmark case, the shadow price of the contracted biomass is always lower than the price of annual biomass at the initial time (see Table 4). This means that it is less costly to supply the bioenergy facility with perennial dedicated biomass (i.e., switchgrass) than to use annual energy crops or wood.

Fig. 2 depicts the geographical origin of biomass for three supplying strategies: "0% contractualization" strategy (sb0), "60% contractualization" (sb60), and "100% contractualization" (sb100). When there is no contractual biomass supply, many counties supply small quantities of annual dedicated crops, except for four that each supply between 10% and 17% of the demand. When the contractual part increases, i.e., when demand for perennial biomass increases, the supply from each county (except for the county where the

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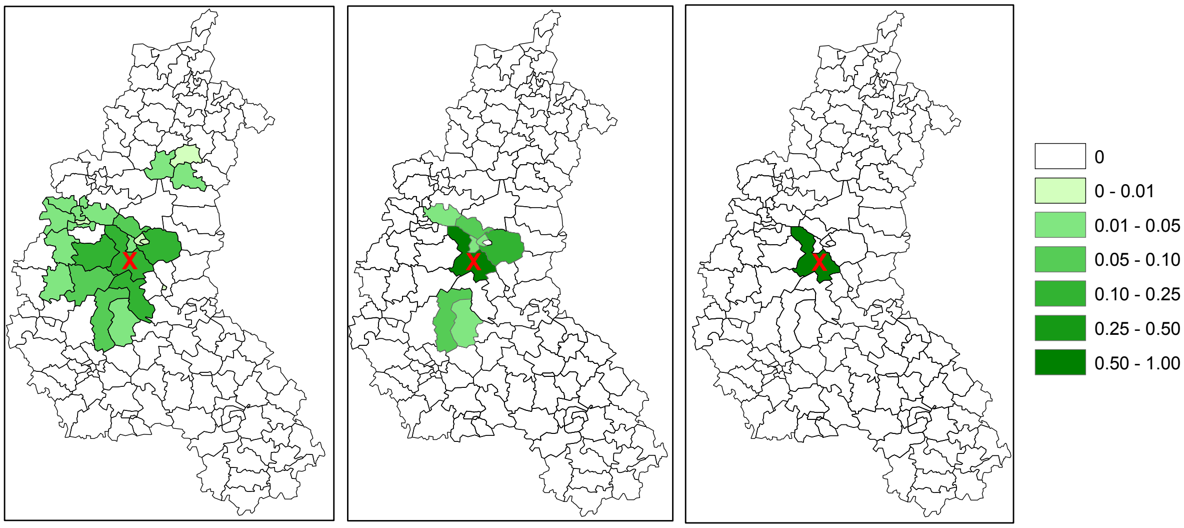
[19] At the region level, for sb0 at $t = 0$, it leads to a decrease of spring barley and peas areas by circa 30%, of wheat and maize areas by circa 5% and to a rise of alfalfa and winter barley by respectively 26 and 19%.

facility is located) decreases and the number of supplying counties actually decreases. The county of the biofuel facility provides the perennial dedicated crops. In the extreme case of total contractual supply, this same county produces only dedicated perennial crops (i.e., switchgrass), satisfying the totality of the plant's demand. From a logistic point of view, the fact that perennial crops are located in a single county, which is the same as that of the facility, should reduce transaction costs.



Contractualization 0%   Contractualization 60%   Contractualization 100%

Fig. 2. Biomass supply per county (percentage of total supply) at $t = 0$

4.2 Viability of the strategies

We next turn to analysis of the viability of the various supplying strategies. Fig. 3(a) exhibits the viability probability of a range of strategies as a function of the profitability threshold price.[20] The horizontal axis corresponds to a continuum of possible values for the constraint threshold $\bar{P}$ characterizing the economic viability constraint (equation (2)). The vertical axis provides the viability probability that allows us to rank supplying strategies. The six curves correspond to the performance of six supplying strategies that vary in their share of contracted biomass, respectively with 0, 20, 40, 60, 80 and 100% of input biomass from perennial crops. Each curve gives the viability probability of the corresponding supplying strategy with respect to the level of the profitability threshold. For any threshold level, the higher the share of contracted biomass, the higher the associated viability probability. Our results are valid whatever the profitability threshold and, thus, are robust to uncertainties for this parameter value.

For every strategy, the lower the profitability threshold, the lower the viability probability. Stronger economic constraints are harder to meet. In that respect, the strategy of total contractual supply sb100 exhibits

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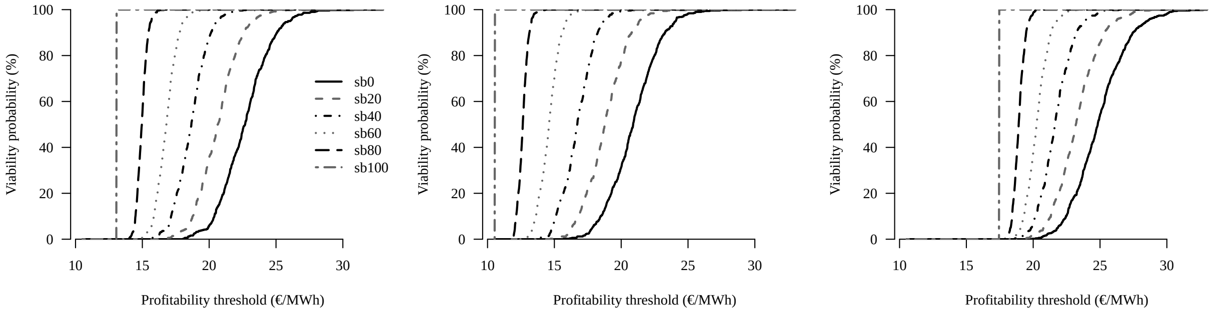
[20] In all the subfigures, the interpretation is the same. We start by describing the benchmark case. The "low contractual price" and "high contractual price" cases are discussed in the next subsection.



(a) Benchmark case **(b)** Low contractual price **(c)** High contractual price

Fig. 3. Viability probability as a function of the profitability threshold for a range of strategies

an extreme behavior, with a nil viability probability for any profitability threshold lower than the contractual price, and a 100% viability probability for any profitability threshold larger than the contractual price. For other strategies, the viability probability varies smoothly with the profitability threshold. For each strategy, the viability probability reaches 100% for some profitability threshold. This provides economic conditions for the robustness of the strategy, i.e., if the actual profitability threshold is higher than that level, the strategy will succeed in all scenarios.

Taken together, our results mean the following. For a bioenergy facility characterized by a given profitability threshold, contracting a larger share of the biomass supply results in higher viability probability. Setting contracts to ensure supply at a given cost is thus a good strategy to achieve the economic and technological viability of a bioenergy facility in an uncertain economic context.

Average total and per energy unit supply costs range respectively from 428 to 651 million euros and from 13.07 €/MWh to 19.88 €/MWh (see Table 6). The strategy consisting in contracting the whole demand is the cheapest.

To better understand these results, we examine their sensitivity to the contractual price, which, in our model, is related to the economic context (in terms of agricultural commodity prices and opportunity cost to produce perennial crops).

4.3 Effect of the initial economic context

We perform a sensitivity analysis of our results to the initial contractual price by computing the opportunity cost of perennial crop supply in different economic contexts. We consider first a "low price" context and then a "high price" context. The prices prevailing when the contracts are signed matter because commodity prices are serially correlated, so periods of low (high) prices tend to be followed by periods of low (high) prices. Even if, in the long-run, prices return to their steady-state distribution, farmers account rationally for the transitional dynamics of prices and accept lower (higher) contractual prices when prices are low (high). Our results are robust to the agricultural commodity price context.

Table 6

Total (in million € for the 13 years horizon) and per energy unit (€/MWh) supply costs for each strategy and initial price context

	sb0		sb20		sb40		sb60		sb80		sb100	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Low price context												
Total supply cost	600	43	547	35	495	267	443	17	397	8	345	0
MWh supply cost	18.33	1.30	16.71	1.06	15.12	0.81	13.54	0.53	12.13	0.25	10.55	0
Benchmark case												
Total supply cost	651	47	601	39	553	30	513	19	471	9	428	0
MWh supply cost	19.88	1.44	18.37	1.18	16.89	0.91	15.66	0.59	14.40	0.28	13.07	0
High price context												
Total supply cost	709	51	675	42	644	32	621	21	598	10	571	0
MWh supply cost	21.64	1.57	20.61	1.28	19.66	0.99	18.97	0.64	18.26	0.32	17.45	0

Notes: Mean and standard deviation over the 500 price scenarios.

Lower contractual price case. We perform the same simulation as in the previous analysis, but starting from a vector of lower agricultural and wood prices (Fig. 3(b)). Comparison of the contractual prices (opportunity cost of perennial energy crops) is provided in Table 7. When the contractual price is low, e.g. if it is set in an economic context characterized by low agricultural commodities prices and thus a low opportunity cost to contract, the viability probability of all the considered strategies increases.

Table 7

Contractual price of perennial energy crop (€/MWh) - Sensitivity to the initial economic context

Initial price level	sb20	sb40	sb60	sb80	sb100
Low contractural price	10.91	10.92	10.83	10.82	10.55
Benchmark case	12.98	12.95	13.33	13.28	13.07
High contractual price	16.94	17.07	17.64	17.66	17.45

An initial context characterized by lower agricultural prices results in lower contractual prices, but also in lower opportunity costs for annual dedicated crops. The viability probability of all strategies improves. Also, lower profitability threshold constraints are met with higher probability. The ranking of strategies, however, is not affected. The strategy that consists in contracting all the biomass supply still meets the viability constraint with a higher probability than for the other strategies.

In terms of type of biomass supplied, silage switchgrass is still the perennial crop contracted by the facility, at a cost ranging from 10.55 €/MWh to 10.92 €/MWh, and produced in the same county on the same soil type.[21] The average annual biomass supply (over the 500 price scenarios) is still composed of whole

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[21] For sb100, switchgrass production leads to a decrease of alfalfa and spring barley areas by 11% and of wheat, winter barley,

plant triticale silage, fiber sorghum silage and wood (mainly softwood chips). However, the share of sorghum increases at the expense of triticale.[22]

The average total and per energy unit biomass supply costs are lower than in the benchmark case for all strategies (see Table 6).

Higher contractual price case. We performed the same simulations as in the benchmark case, but starting from a vector of higher agricultural prices corresponding to the 9th decile of 1993–2007 prices (Fig. 3(c) and Table 7). The conclusions still hold when the contractual price is high, though the profitability threshold of all strategies increases.

In terms of type of biomass supplied, silage switchgrass is still the perennial crop contracted by the facility, at a cost ranging from 16.94 €/MWh to 17.66 €/MWh, and produced in the same county on the same soil type.[23] The average annual biomass supply (over the 500 price scenarios) is still composed of whole plant triticale silage, fiber sorghum silage and wood (mainly softwood chips). However, the share of triticale and wood increases at the expense of fiber sorghum. In addition, the standard deviation of wood and sorghum supply over the 500 price scenarios increases. Whole plant triticale is still the non-contractual dedicated crop delivered to the facility at $t = 0$ in the supplying strategies sb0 to sb80, and it is grown on the two most fertile soil categories of the region.[24]

The average total and per energy unit biomass supply costs are higher than in the benchmark case for all strategies (see Table 6).

5 Discussion and conclusion

Meeting the increasing targets of bioenergy production without harming the environment requires development of viable second generation bioenergy chains. Their viability depends on both the local availability of biomass and the profitability of production. These elements are strongly influenced by the economic context and uncertain agricultural commodity prices, and the resulting opportunity cost of producing energy crops.

In the present paper, we use a stochastic viability approach to examine the economic and technological viability of a second generation bioenergy facility. We consider a technological constraint on biomass supply, and an economic constraint on supply cost. The profitability threshold characterizing this latter constraint is treated as a parameter in the sensitivity analysis. We examine the viability probability of various supplying strategies, i.e., the probability with which these strategies respect the constraints over time. We show that the

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rapeseed and maize by 2 to 4%.

[22] When fiber sorghum silage is delivered to the facility, it is mainly grown on a less fertile soil category. At the region level, for sb0 at $t = 0$, the substitution of fiber sorghum and whole plant triticale to respectively maize and spring barley leads to a decrease by 30% of maize area and by 21% of spring barley area.

[23] For sb100, switchgrass production leads to a decrease in maize, sunflower, and wheat areas by 6 to 4% and to an increase in spring barley areas by 6%. It is noteworthy that for this price context, neither alfalfa nor peas are grown.

[24] At the region level, for sb0 at $t = 0$, the substitution of whole plant triticale to respectively spring barley and wheat leads to a decrease of spring barley areas by 42%, of wheat, maize, and sunflower areas by 2 to 3%, and a slight increase of rapeseed by 4%.

strategy of contracting total biomass supply with perennial dedicated energy crops maximizes the viability probability.

From a decision making point of view, our results suggest that the viability of second generation bioenergy facilities strongly depends on the availability and cost of local biomass supply, which, in turn, is strongly affected by other commodity price uncertainties. Setting contracts that ensure both supply of the required quantity and its cost is an efficient strategy to limit the risk of non-viability related to the uncertain agricultural commodity prices, at least when such contracts can be set at a sufficiently low price with respect to the profitability threshold.

An interesting result of our modeling exercise is that both the contracted perennial biomass and the non-contracted annual dedicated biomass are produced mainly on the best quality land across the region. Second generation biofuel facilities may induce competition with conventional crops for the most productive land .

In this study we assume that the contractual price will equal the opportunity cost of the last energy unit delivered to the facility. However, this is probably underestimated for two reasons. First, in our simulations, dedicated biomass is sometimes grown on 100% of the crop growing farms area, whereas farmers are generally reluctant to introduce mass production of new crops. Second, farmers will probably ask for a price revision over time since it is a long-run contract. We also do not consider farmers' liquidity constraints or risk aversion. Bocquého and Jacquet (2010) suggest that the combination of a guaranteed fixed price and a subsidized loan to finance perennial crops establishment cost enhances the adoption of such crops by farmers.

Last, as the size of facilities influences their optimal location and profitability (Kocoloski et al., 2011), future research could examine how the size of the bioenergy facilities modifies their viability in a given region.

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