Food, feed, fuels, and the environment : delimit the feasible production set of the French agricultural system.

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Abstract

Using an agricultural supply model developed for the European Union, we assess the production potential to satisfy two objectives, one related to food calories, the other to biofuels replacing fossil fuels. For energy-related production, we distinguish between gasoline and diesel substitutes. The production set is provided for France, by varying the thresholds for food calorie and bioenergy simultaneously. We find that France shows a large potential of biomass resources that allows a great margin for action where food and energy security could be compatible and associated economic viability and environmental protection. If the feasible set reveals a high production potential in the both food and energy dimensions, the implicit high prices associated with the two constraints show that this potential could only be achieved at the cost of substantial structural and spatial changes of the agricultural production system. We show in particular the emerging tension on animal production and even more on animal feed, and we find that food and bioenergy production targets jointly induce significant greenhouse gases emissions reductions.

Keywords: Food production, biomass for energy, France, land conversion, agriculture sourced GHG emissions;
Abbreviations: EU: European Union; GHGE: Greenhouse gases emissions; DM: Dry Matter; SRC: Short Rotation Coppice;

1 Introduction

In the European Union, as in many EU member states, public policy projects are outlined in an attempt to respond to the multiple arising challenges such as food security, energy transition and rising energy demand, along with the transversal objective to reduce greenhouse gases emissions and mitigate the effects of climate change. These concerns are at the crossroads of several important policy areas involving agriculture, energy and the environment which are interdependent and require policy coherence to ensure a balanced and sustainable development. For instance, biomass, while having various end-uses and competing for already pressured production resources (land, water), remains the primary source of renewable energy in the European Union, accounting for a 60% share, mainly consisting of domestic forestry products and by-products (Scarlat et al. (2019a)). Bioenergy is also one of the most promising sources of renewable energy (IEA (2017)), although the share of agricultural crops and co-products, dedicated energy crops and waste reuse would have to increase to meet European targets, adding pressure on our agricultural systems to meet multiple purposes: food, feed and energy production, and a significant role in the mitigation of GHGE and the protection of the environment.

A key aspect of the EU renewable energy policy is to decrease the greenhouse gas intensity and increase the share of renewables in the transport sector, through the promotion the use of biofuels

(European Parliament (2009), European Parliament (2018)) which still account for only a fraction of all bioenergy consumed in the EU. At least 14% of fuel consumption for transport should come from renewable sources by 2030, with a careful focus on the sustainable production of biomass as various studies have highlighted the potential impacts of complying with bioenergy targets on food markets, land use change and scarce resources with competing uses, namely food and feed supply (Rulli et al. (2016), Scarlat et al. (2013)). The share of first-generation is thus limited while advanced biofuels must reach at least 3.5% of final fuel consumption in 2030. However, the question still remains whether the EU can ensure a sufficient level of biomass production for food, feed and fuel supply, within the boundaries set by physical and policy constraints, and with which economical and environmental impacts.

As a leading country in the agricultural and forestry sectors in the European Union, the case of France is worth investigating. It is also believed to have the largest potential for biomass resources and biomass use for energy. The agricultural system in particular shows an under exploitation of its diverse resources available for energy, with various end-uses. In 2017, 55.6% of 26Mtoe of renewable energies were produced from biomass in France, but only 16% from agricultural biomass alone, divided in 3 sectors: biofuels (2.6Mtoe), biogaz (0.9Mtoe) and the combustion of residues from agriculture and agro-industry (0.6Mtoe) (MTES (2019)). Still, additional efforts will be necessary for France to meet its national targets as fixed by the 2015 Energy Transition Law for Green Growth (LTECV, Loi transition énergétique pour la croissance verte): 23% of renewables in final energy consumption in whole in 2020, then 32% in 2030, and, more specifically, 15% of renewable energy in the final consumption of the transport sector in 2030 which would amount to 5Mtoe (209PJ) according to projections (ADEME et al. (2019)). The French bioeconomy policy package and the European Union one include similar related goals: reduce dependence on imports for food and for energy, and foster the development of new markets.

We propose to study to which extent the current agricultural production system of France could meet such ambitious objectives, in terms of biomass supply for both food calories and energy, without inducing major technical and structural changes. Identifying the availability and scale of resources across territories is crucial to determine the viability of our policy responses to the issues at stake and the role of biofuels particularly. We choose to focus on second-generation biomass feedstocks as a development pathway to use and produce biomass more efficiently (Muscat et al. (2019)), to produce more effective biofuels (in terms of greenhouse gases emissions reduction) and to investigate the role of non-food feedstock in alleviating the competition for agricultural biomass and the pressure on the environment, although the competition for land can remain. We chose to represent the potential of French agricultural biomass production for road transport biofuels as they are expected to play a significant role in the country's energy transition (Colonna et al. (2020)), but there are obviously a variety of potential other end-uses for the biomass production we are considering.

Our analysis relies on the supply-side agricultural model AROPAj in which we introduce several perennial crops based on sourced biological data and management optimization. We then impose simultaneous targets of biomass intended for food calories and biomass intended as feedstock for advanced fossil fuels substitutes. Regarding food production, we only consider the total net calorie balance, based on the calorie content of agricultural products as document by the FAO, but we control for the share of these calories brought by proteins. The transformation of biomass into energy is divided into two competing groups, producing a substitute for gasoline (Lignocellulosic ethanol) or a substitute for diesel fuel (Biomass to Liquids or BtL). The conversion coefficients of biomass into fuel are based on IEA data and projections, as the development of advanced biofuels remain at a demonstration or early commercial stage and still rely on technical innovation. Depending on estimations, we are looking at a 2025-2035 horizon. This analysis incorporates a third objective, which is the quantity of greenhouse gas emissions of agricultural origin in an effort to assess the potential for emissions reduction in the sector under constraint and a net GHGE balance for biofuels.

This article will focus on bounding the solution space of the French agricultural system in terms of the production of biomass for both food calories and biofuels, including trade-offs related to animal feed, and then to contrast this potentially feasible set in terms of economical and environmental outcomes, including efficiency, costs, regional variability, land use changes and emissions.

2 Methodological elements

2.1 Model

The results presented in this article rely on the agro-economic supply-side model AROPAj (see Jayet et al. (2019) for a more thorough description). AROPAj is a linear programming model describing the annual choices of the European farmers in terms of land allocation among numerous crops, vegetables and animal production and other activities, as well as the associated pollution. AROPAj also has the merit of accounting for animal through various sources (grass, on-farm consumption of cereals, forage, concentrated feed). The farmers are clustered in farm groups within each region based on a statistical representation of the techno-economic characteristics observed in FADN individual data to represent a wide array of technical constraints and behaviors among European farmers. The current version of the model is based on the year 2012 and we use it in aggregate mode, which aims at selecting the level of all supply variables for each farm group to maximize the total gross margin of the system, subject to several constraints related to cropping requirements, animal breeding, land endowment and CAP directives. The scope of the model is EU-27 but we will only focus on the case of France in the following.

For the purpose of our analysis, the AROPAj model is augmented by allowing for the net food calories (accounting for on-farm consumption) and biofuel quantities produced to be constrained across farm-groups. The economic behavior of the agricultural sector is thus assumed to be summarized by the following optimization program:

$$\begin{aligned}
&\max_{\{x_k, y_k\}_k} \sum_k \pi_k(x_k, y_k, \theta_k, \phi) && \\
&s.t. \quad \forall k : \{x_k, y_k\}_k \in \mathcal{A}_k(\theta_k, \phi) && \\
&\qquad \sum_k b_k x_k \geq Qcl && (\lambda) \\
&\qquad for\, j = 1,2 : \sum_k e_{jk} y_{jk} \geq Qnr_j && (\rho_j) \\
&\qquad \forall k : y_{1k} + y_{2k} \leq x_k &&
\end{aligned}$$

where x_k denotes farm group k vector of activities, π_k is its gross margin, and the production set $\mathcal{A}_k$ is determined by θ_k and ϕ representing respectively group-specific and common parameters. In this formulation of the problem, we bring in the variables y_{jk}, the quantities of biomass intended for each of the two bioenergies of substitution of fuels of fossil origin (indexed by j). The terms λ and ρ_j designate the Lagrange multipliers associated with the constraints of interest for the rest of the article (i.e. the implicit prices of the threshold quantities). The parameters b designate the factors for converting biomass into calories suitable for human consumption. The parameters e designate the factors for transforming biomass into energy, formally of zero value for the variables not concerned with energy in the maximization program.

The overall farming system is also constrained to produce a minimum quantity of dietary calories represented by Qcl, knowing activities in x_k are weighted by b_k, which is the vector of contribution to the net balance of food calories of each product, and it achieves a targeted amount of biofuel production Qnr_j, denoting by y_{1k} and y_{2k} the share of products that count towards the respective production of biodiesel and bioethanol, weighted by crop and fuel dependent conversion coefficients, in vectors e_{jk}. Targets Qnr_1 and Qnr_2 are to be reached simultaneously by the system, relevant resources counting towards one type or the other.

	Crop type and management	Reference yield (tDM/ha)	Price (€/tDM)	Biodiesel yield (toe/tDM)	Ethanol yield (toe/tDM)
Miscanthus	Harvested annually Optimized rotation length	18	70	0.24	0.19
Switchgrass	Harvested annually Optimized rotation length	15	65	0.24	0.19
Eucalyptus	SRC over 35 years Harvested every 10 years	11	67	0.24	0.19
Black Locust	SRC over 35 years Harvested every 10 years	8	67	0.24	0.19
Poplar	SRC over 25 years Harvested every 7 years	10	67	0.24	0.19
Willow	vSRC over 20 years Harvested every 3 years	10	67	0.24	0.19
Crop residues	Hard wheat straw	4.8	35	0.23	0.15
	Soft wheat straw	6.0	35	0.23	0.15
	Barley straw	5.5	35	0.25	0.16
	Oats straw	3.2	35	0.25	0.16
	Rye straw	4.6	35	0.23	0.15
	Other cereals straw	3.8	35	0.23	0.15
	Corn stover	8.1	35	0.23	0.15
	Rapeseed straw	5.9	35	0.23	0.15
	Sunflower straw	5.6	35	0.23	0.15

Table 1. Mobilisable biomass resources for bioenergy production in AROPAj.
The reported yields for crop residues are national averages from the results of our calculations.

2.2 Introduction of bioenergy crops into AROPAj

Advanced biofuels are manufactured from various feedstocks whose use is assumed not to compete with food supply. These include forestry products, industrial and municipal waste, and lignocellulosic biomass from perennial crops and agricultural residues, on which we will focus in our study. Although the reuse of wastes, by-products and residues is particularly encouraged, these energy crops exhibit the largest potential as alternatives to the food crops used in first generation biofuel processes (Smeets et al. (2007)). They supposedly produce more dry matter, more efficiently, than traditional crops and present ecological properties regarding water use, soil erosion and ground water pollution. They could offer a high net energy production, for a low level of fertilization and work inputs. Expenses are rather associated with implementation costs and mechanical harvesting.
We take advantage of the agricultural supply model AROPAj by accounting for the by-products associated to existing AROPAj agricultural activities (cereals and oilseeds straws, corn stover) and by including various woody and herbaceous perennial crops dedicated to the production of biomass for energy in the farm-groups choice sets. Table 1 summarizes the biomass resources to be used for bioenergy included in AROPAj and our assumptions.

Miscanthus x Giganteus and Switchgrass are introduced in the AROPAj model by making use of the "Faustmann" rule to compute net present values (Bourgeois et al. (2014)). Potential yields are econometrically correlated to the farm-group cereal yield and allow for us to determine the optimal duration of rotation so as to maximize the gross margin of cultivating the crop over time with annual harvests. From there, we can calculate the average yield of dry matter per year and the discounted costs at the farm-group level (see Ben Fradj et al. (2016) for additional methodological details). This is of course an imperfect estimation, firstly because of the lack of data, although it can be considered as a reasonable representation of feasible production observed for these crops under favorable conditions.

We include 4 other perennial crops which have been widely explored for bioenergy and are susceptible to be grown as energy crops in Europe: Eucalyptus, Black Locust, Poplar, and Willow. As such we can explore diverse sources of biomass in France, in terms of both profitability and biomass production efficiency. To document these crops in the model, we follow the crop management itinerary advised by the LIGNOGUIDE project publications (Besnard et al. (2014), RMT Biomasse Energie (2018)). We compute yields based on an econometric relation between Willow and Oat yield, adjusted for the other crops to meet an average reference yield. Perennial crops such as these 4 woody crops grow in similar soil and temperate weather conditions as oat. They can be grown in poor-quality soil and they show great resistance to rain and cold, apart from Eucalyptus which shows more sensibility to cold and certain types of soil. We thus restrict the possibility of growing Eucalyptus to regions with suitable conditions: the Atlantic coast up to Brittany, as well as the southern Mediterranean area (Melun & Nguyen The (2012)).

To determine agricultural by-products yields, we rely on an existing methodology (Scarlat et al. (2010, 2019b), Monforti et al. (2015)). We use documented crop-specific correlations to compute residue-to-yield ratios based on farm-groups known crop yield. We then calculate the potential yield of crop residues in each farm-group. We use default residue collection rates of 40% for cereals and 50% for corn, rapeseed and sunflower which complies with technical constraints and is in line with the average environmental requirements for the preservation of organic carbon stocks and agricultural properties of French soils according to the literature previously cited as well as national recommendations(FranceAgriMer (2016)). Note that straws and stovers have end-uses outside of bioenergy we do not consider here.

IRENA (2016) projects the cost of biomass feedstock for 2nd generation biofuel plants to range from 2 to 4 €/GJ, that is roughly 25-70 €/tDM, in the 2025-2035 horizon. Based on the usual assumptions one can find in the relevant literature, for example 80 €/tDM for miscanthus, and on the evolution of wood-energy prices, we chose biomass prices at the high end of the range for woody and grassy energy crops, in line with average equivalent prices in moderately favorable growing regions, that is prices that would be needed for the average margin associated with perennials crops to reach that of conventional crops (RMT Biomasse Energie (2018)). We chose lower prices for agricultural residues because we ignore any mobilization costs for residue collection in our model.

2.3 Model implementation

- **Data :**

Quantities related to food calories are expressed in metric tons of soft wheat equivalent (t_{sweq}), based on the caloric content for each product as documented by FAO reports (FAO (2003b)), with respect to that of soft wheat. We further constrain the share of these food calories that are brought by proteins, whether animal or vegetable, to remain above 11% in the aggregate production, corresponding to the minimal level of intake recommended by the FAO for human safety although in most occidental countries the consumption and production of proteins ranges much higher. The main goal is to track changes in domestic food production, as the country's dependence on imports for proteins already is one of the main issues at stake for its food security. However, the constraint was never found to be binding in any of our simulations. We used FAO data and methods to calculate protein content in terms of caloric yield (FAO (2003a)), as well as data on animal feed from French oilseed, oil and legumes interprofessional association Terres Univia.

Both biodiesel and bioethanol production are expressed in tons of oil equivalent (toe), which measure the amount of energy with respect to the calorific value of crude oil. For reference, a ton of ethanol is 0.64 toe while a ton of biodiesel is 1.05 toe. The fuel yield coefficients are estimations of the conversion efficiency of currently developing technologies transforming lignocellulosic biomass into biofuels, that is, mainly, BtL biodiesel and lignocellulosic ethanol. Note that we only introduce the transformation of biomass to biofuels in AROPAj through this single conversion coefficient, without taking into account market considerations, nor transportation or processing costs. We assume that the entire stock of biomass produced will be meeting the demand of the biofuel industries and bought at a fixed price. We rely on the IEA-ETSAP technologies data and projections in a 5 to 10 years time horizon to determine fuel yields (IRENA (2016), see also IEA (2011) and ANCRE et al. (2015) for background information). Lignocellulosic ethanol currently is at an early commercial stage, while thermochemical processes such as BtL are usually at a pilot or demonstration stage.

Greenhouse gas emissions computations in the model are based on IPCC guidelines (IPCC (2001)) and account for CH_4 emissions from animal production (enteric fermentation, manure management) for each animal category, and from rice cultivation, and N_2O emissions from various sources: synthetic fertilizers and manure application, N fixation by crops, leaching, crop residues, pastures (De Cara et al. (2005) for more details on emissions accounting in AROPAj).

- **Scenarios :**
  We conduct simulations by varying the level of 2 parameters of interest: QCL, the net calorie production threshold, and Qnr_j, the targeted amount of j biofuelsl. We assume the diesel to gasoline ratio to remain constant and equal to 3 (in accordance with EU Commission (2016) projections) in all simulations so that the target for bioethanol, which we denote Qnr_2, moves linearly with Qnr_1, the designated threshold for biodiesel, and we can equivalently realize simulations varying the total amount of biofuel produced simultaneously: $QNR = Qnr_1 + Qnr_2$.

  The benchmark situation here is when both QCL and QNR, and the associated constraints, are null, which does not mean that no calorie production nor no biomass production will result from the optimization program, depending on their profitability only. We then increase both targets incrementally until the model fails to be solvable. This process allows us to determine the boundaries of the feasible production set for the country, in terms of calories and biomass production, in a technically and economically realistic environment (under the initial conditions), and to explore the outcomes within this area. The analysis is prospective, and does not account for potential price effects nor climate change impacts.

  The maximization of domestic biomass resources is instrumental for energy security but also to allow the development of the advanced biofuels industry. The yields reported in Table 1, undoubtedly lower than for 1st generation biofuels technologies highlights the challenge of 2nd generation biorafineries, because they need to be able to secure their feedstock supply in massive quantities from disseminated biomass resources. As such, we will further explore scenarios in which the focus lies in biomass production while the food calories production is only growing slowly ($QCL = 65000$ represents a 5.2% increase with regards to the benchmark situation) to account for population growth and increased food security.

  Note that limitations are set to prevent radical or unlikely solutions. The livestock adjustment rate, which is the exponential rate of change in the animal capital with respect to its initial value is bounded to 25% for each cattle category, sheeps, goats, swines and poultry. Livestock is evaluated in livestock equivalent unit (LU) based on FADN. Within each farm-group, the area dedicated to each energy crops cannot exceed 20% of the utilized agricultural area (UAA) included in AROPAj and their total aggregated area within a farm group cannot go over 60% . The underlying assumption is that we would not observe a complete disruption of the agricultural production system and a collapse of food supply over the course of a one-year period. Also, because revenue flows from energy crops are actually one or several years apart, we would expect them to be grown in parallel with conventional activities within farms.

3 Analysis of results

3.1 Food and fuel joint production potential

Although not diverted from food supply, energy crops still compete with conventional crops for production resources and, mainly, land, assuming that if energy crops were found to be economically profitable and in demand, there would be no reason for their production to be confined on marginal and poor quality lands.

Figure 1 illustrates the jointly reachable biofuel and calories targets for France under the current economic and technical conditions as represented in the model. Under nonbinding food calories requirements, France could produce up to 180 MtDM of biomass, to be potentially converted into 40 Mtoe of biofuels, which is equivalent to the annual national energy consumption in the road transport sector in the past years. (EU Commission (2019)). Table 2 contrasts results in terms of revenues and competing activities for several points in the boundary area in comparison to the unconstrained case ($QNR = 0, QCL = 0$), where the production of both calories and biofuels is only driven by economic profitability. It also highlights possible synergies between food and fuel by enhancing the use of agricultural co-products such as straws, although their contribution is small when bioenergy production is high and land is diverted away from cereals.

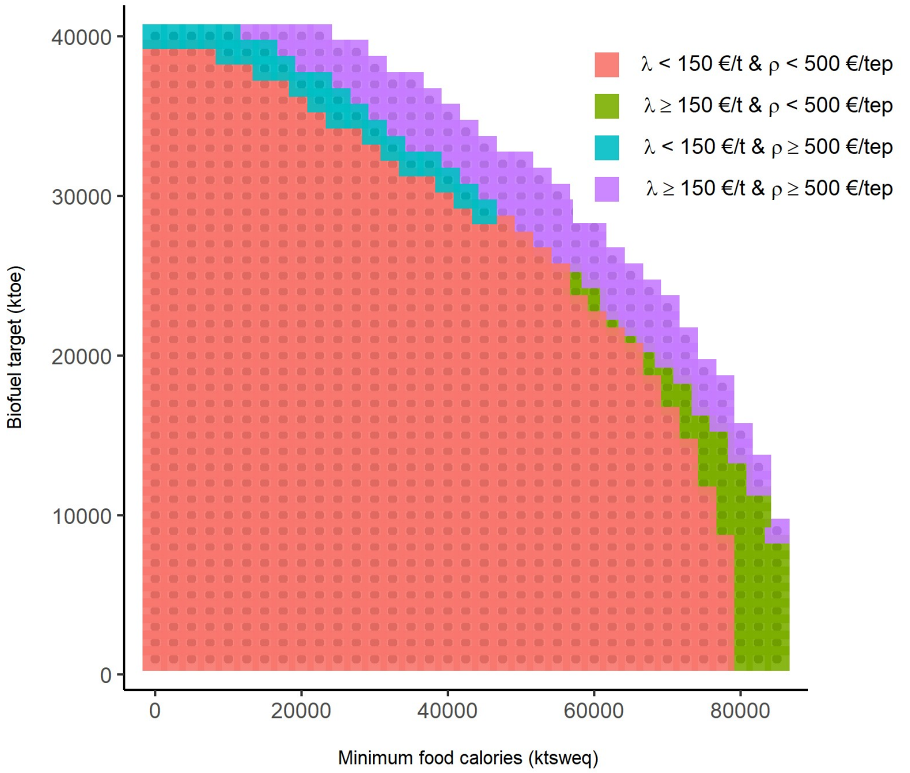

Figure 1. Production frontier attained with 1138 simulations given the biofuel and food calories thresholds, along with the shadow prices λ and ρ, associated respectively to the calories constraint and to the biodiesel constraint, expressed in comparison to average prices for soft wheat (150 €/t) and for biodiesel (500 €/t, excluding procurement costs).

The production set shown in Figure 1 is divided in four areas to highlight the area in which the shadow prices associated to the calorie constraint and to the biofuel constraint[1] are somehow

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[1] It ought to be noted that we have, by structure, an equivalence between the dual value associated to the minimum

QNR	QCL	Gross margin	Calories production	Livestock	Energy crops production	Residues use	Biodiesel production	Bioethanol production	Share of French transport energy
ktoe	kt_{sweq}	G€	ktsweq	kLU	ktDM	ktDM	ktoe	ktoe	%
0	0	33610	61770	16557	12537	30013	7655	2550	20.4
0	85000	30463	85000	12778	193	31963	5796	1932	15.5
10000	80000	32134	80000	13734	13790	30885	7500	2500	20
20000	70000	31127	70000	13306	61100	28373	15000	5000	40
30000	55000	26614	55000	11831	111024	23258	22500	7500	60
40000	20000	25067	20000	12965	164302	14795	30000	10000	80

Table 2. Detailed solutions for joint production points close to the frontier, in terms of activities and revenues at the national level. We use a reference level equal to 50 Mtoe for total energy demand in transport in France (based on EU Commission (2019)).

comparable to observed values : an average farm gate price for soft wheat, and a refinery price for biodiesel based on biomass acquirement, excluding procurement and transformation costs (the comprehensive importation price of biodiesel in France usually ranges from 800 to 1000 €/toe).

As cautious as we should be regarding this comparison between the shadow prices and actual prices, these dual values illustrates the extent to which each of the constraint is binding and thus the burden for the agricultural system to produce more biomass for food or energy from a certain point of production, and we can observe that the largest part of the production set we have determined, up to 25Mtoe of biofuel and 60 Mt_{sweq}, appears like reasonably achievable targets to be reached in a potential equilibrium, in the current economic and physical conditions of French agriculture, with or without prioritizing one of the 2 targets. Keeping the quantity of food calories produced constant, with regards to the benchmark, up to 25Mtoe of biofuels could be produced, only through structural modifications of the cropping systems in place. However, the dual values, in particular for the biofuel constraints grow exponentially as we go up to the frontier. These dual values represent the cost, in terms of the loss in the total gross margin of the production system, of the production of the additional biomass associated with the extension of the constraints related to biofuels. Figure 2 depicts the marginal cost of primary energy production we can infer from the dual value associated the constraint on biodiesel. These values stem from the adjustment of the whole system, the production cost and the opportunity cost of growing biomass, we do not isolate the specific cost terms associated to this production. Also, biomass is remunerated by fixed prices in our model, corresponding to about 3.7 €/GJ for dedicated energy crops and 2 €/GJ for crop residues. According to various estimates, cost of the feedstock could represent 40 to 70% of the total production cost of advanced biofuels (Colonna et al. (2020), Hamelinck (2006)), their price being one of the main determinant of their acceptability. High implicit prices for biomass could prove incompatible with their effective transformation into biofuels which can be incorporated into refined products. For means of comparison, the selling price of conventional biofuels ranges slightly above 20 €/GJ, equivalent to about 0.6 €/L.

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target to reach for biodiesel production and the dual value associated to bioethanol production, which is why we only represent one of the two. In our model, an amount of biofuel is unambiguously translated into an amount of biomass by a fuel yield coefficient and bioethanol and biodiesel are assumed to be made from the same feedstocks. Hence, the implicit price ρ_j is equivalent to the change in gross margin induced by the lesser amount of biomass feedstock needed when relaxing the required amount of biofuel j, it then only depends on j's biomass to energy conversion efficacy. As presented in Table 1 (rounded coefficients), the fuel yield for the biodiesel process, when measured in toe/tDM, is slightly superior to that of lignocellulosic ethanol, by a coefficient approximately equal to 1.29. We indeed find the same linear relationship between the dual values in our results, which writes: $\rho_1^* = \frac{\partial \Pi^*}{\partial Qnr_1} \simeq 1.29 \frac{\partial \Pi^*}{\partial Qnr_2} = 1.29 \rho_2^*$, Π^* being the value function with the optimal solution.

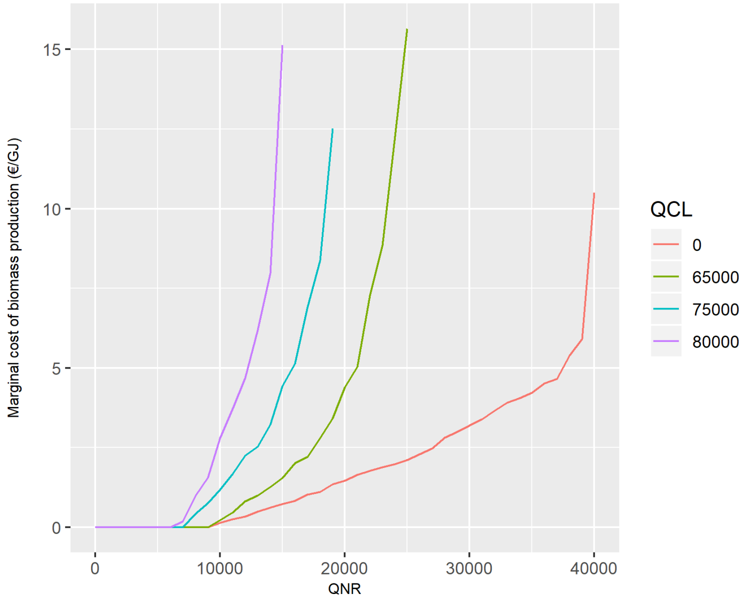

Figure 2. Evolution of the dual value associated to the constraint on the production of biodiesel with growing biofuels global target (QNR) translated in terms of biomass primary energy need for biofuel production, for several levels of calorie production.

3.2 Land use changes at the national and regional scales

Quite ambitious targets could potentially be reached on both fronts but would potentially impact food and energy prices (see dual values) and require great structural, and geographical, changes in the French agricultural production system. Figure 3 illustrates the changes in the area dedicated to several major activities when the production of dietary calories is constrained to increase and for various levels of biofuel production. We can see how higher biomass requirements for biofuel exacerbate the land conversion patterns induced by an increase in calorie production (see, for example, the evolution for non-binding constraint $QNR = 5000$ ktoe). Calories requirements complicate biomass production efficiency and its potential to increase, and conversely, because both food and energy crops aim at superseding others on highly productive lands and to taking up land used to produce calories inefficiently, that is, grasslands, compensated by a substitution with other animal feed sources, namely forage and on-farm consumption of cereals. Hence, animal production would undoubtedly be affected negatively by this twin-race for efficiency and surface area and the animal population would fall when the calorie threshold becomes too challenging.

Notice that the share of fallow lands could increase greatly with the food production level, although this effect is moderated by biomass production for energy. The maximal technical potential of calorie production ($QCL = 85000$) has also proven compatible with the production of up to 9Mtoe, through the use of crop residues but also the use of lands that could not be used for food production. Even if costlier, this could support the subsidized cultivation of energy crops on lands unsuitable for food crops, but it might penalize the production and the consumption of biofuels. A biofuel target of 5Mtoe could potentially be met by dedicating slightly less than 1Mha to energy crops, but meeting high bioenergy targets would however potentially take up more than half of the country's utilized agricultural area. The insertion of dedicated energy crops into existing agricultural systems would then be crucial to balance their economic and environmental viability with moderate land use changes.

Figure 4 shows the potential impacts on land allocation at the regional scale of increasing the production of biomass for biofuel, increasing the amount of dietary calories slightly above

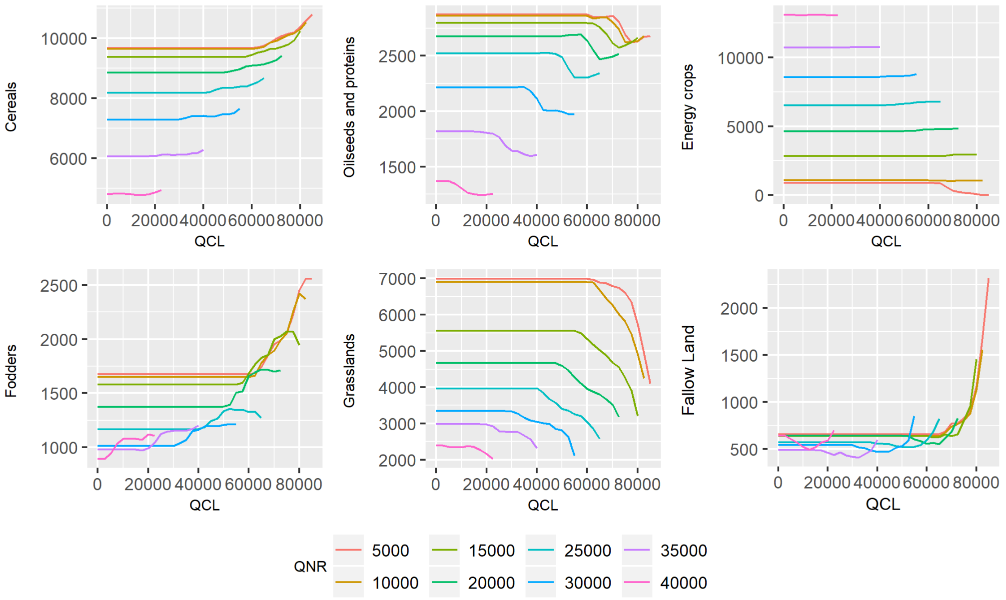

Figure 3. Evolution of the area sharing (in 1000 ha) of cereal crops, oilseeds and proteins, energy crops, fodders, grasslands (permanent and temporary) and fallow lands for various calorie thresholds, ranging from 0 to 85000 kt_{sweq}, and biofuel targets, from 0 to 40000 ktoe (split between biodiesel and bioethanol according to a fixed ratio). As background, the total UAA of mainland France in AROPAj is 23.6 Mha.

the benchmark level ($QCL = 65000$). We observe a clear decline in the share of agricultural area dedicated to grasslands as well as the displacement of cereals crops in favor of perennial crops in some regions. Changes in animal feed plays a key role in adjusting to the land requirement of demanding constraint, freeing up space for energy and food at a lesser cost, in terms of aggregate revenue loss, than displacing conventional crops for example. As such, animal activities appear as the main adjusting factor to combine food and energy production. However, note that while we cap the livestock adjustment rate in our scenarios, the model assumes flexibility between grassland and arable land, and the impacts of this conversion process on economic and environmental assessments could and should be further investigated.

While the amount of cereals produced decreases with biofuel production, we can observe a spatial recomposition, cereal production gradually concentrating in traditional grain-producing areas while the cultivation of energy crops becomes more and more predominant in the west and south of the country to produce biomass more efficiently. More specifically, when the biofuel target becomes more challenging to reach, the system prioritizes the switching of cereals for high-yield annual crops, miscanthus and switchgrass, as well as, in smaller proportions, poplar in central regions and eucalyptus in Brittany and other regions with oceanic climate, while the share of land dedicated to more remunerative energy crops increases more slowly (as willow and black locust). This hints how biomass production efficacy could be improved without disrupting the core of the agricultural system, by enhancing the profitability of higher biomass yield crops.

Figure 5 further illustrates the potentially available biomass production, by region and by type, in two scenarios: the unconstrained benchmark case, first, and a situation combining a slight increase in food calories production and an ambitious target of biofuel production. We can observe the important role of agricultural residues, even when the model is unconstrained. However, this source has less potential for expansion, although it remains stable because of the demand for food calories, and energy crops constitute the main biomass feedstock to be used for biofuel transformation when we impose a high production objective. Relevant findings for the development of biorefineries could be that almost all regions, expect the South of France, show a significant potential for biomass production, although the type of feedstocks to be dealt with varies (residues, grassy crops, woody crops) and their spatial distribution do not necessarily overlap. In our model results, high biomass supply does not fundamentally displace geographically cereals and oilseeds production, hence agricultural residues availability, from France's major agricultural regions. Energy crops, conversely, would take over grasslands in traditional animal breeding regions and, to a smaller extent, fallow or underused lands in regions with low agricultural exploitation. The stability and the concentration of biomass resources in a relatively close area are both crucial for the establishment of effective biomass supply chains and the growth of bioenergy use (ANCRE et al. (2015)).

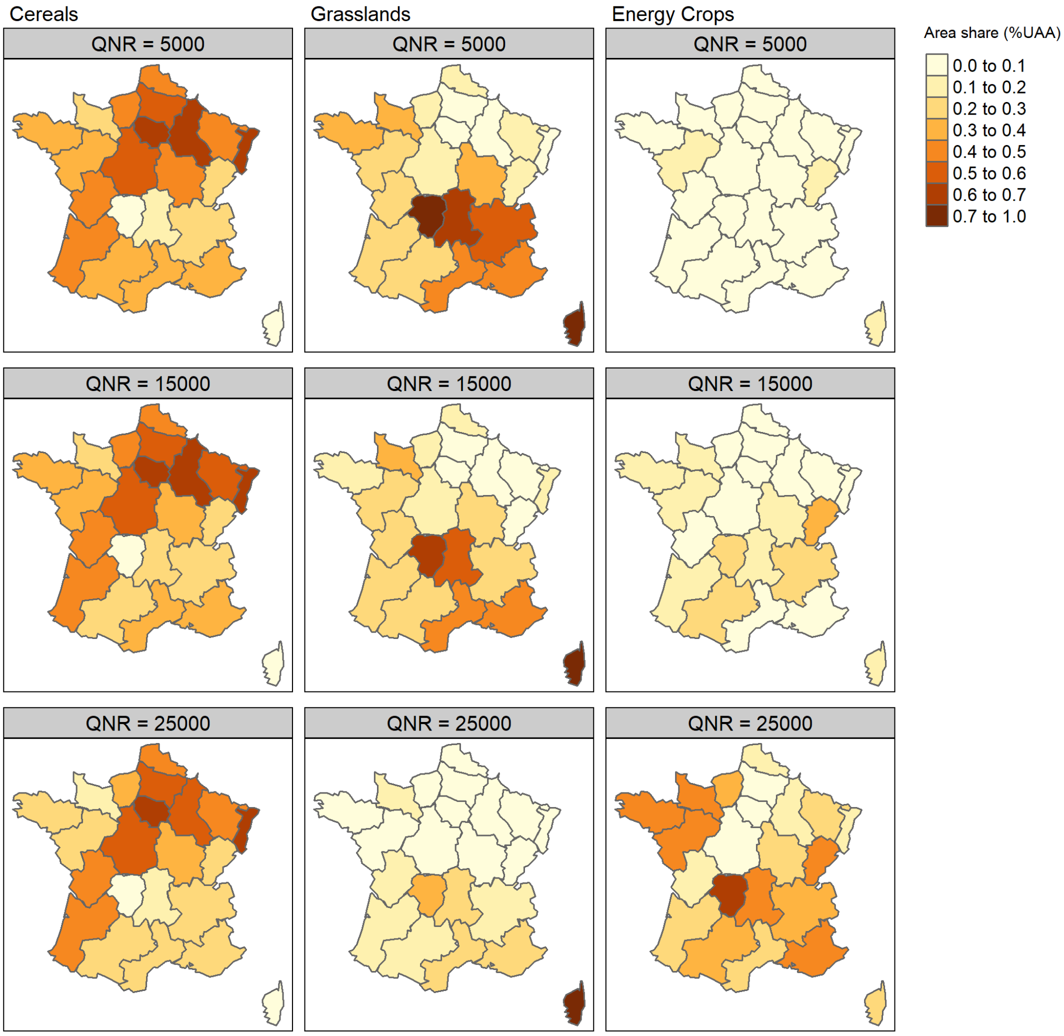

Figure 4. Evolution of the regional average area share dedicated to cereals (soft and durum wheat, barley, oats, rye, maize, and other cereals), grasslands (permanent and temporary) and energy crops (miscanthus, switchgrass, eucalyptus, black locust, poplar, willow) when increasing the biofuel target, for a given calorie threshold QCL=65000 kt$_{sweq}$.

3.3 Impacts on agricultural GHG emissions

We further investigate the impact of the introduction of dedicated energy crops in the agricultural system on greenhouse gases emissions. Figure 6 depicts changes that could be observed in agricultural-sourced emissions of methane and nitrous oxide given the targeted biofuel amount and the level of calories required (moderate increase in food supply from baseline scenario level, i.e. 61770 kt$_{sweq}$). This illustrates several patterns that could be at stake in adjusting the agricultural

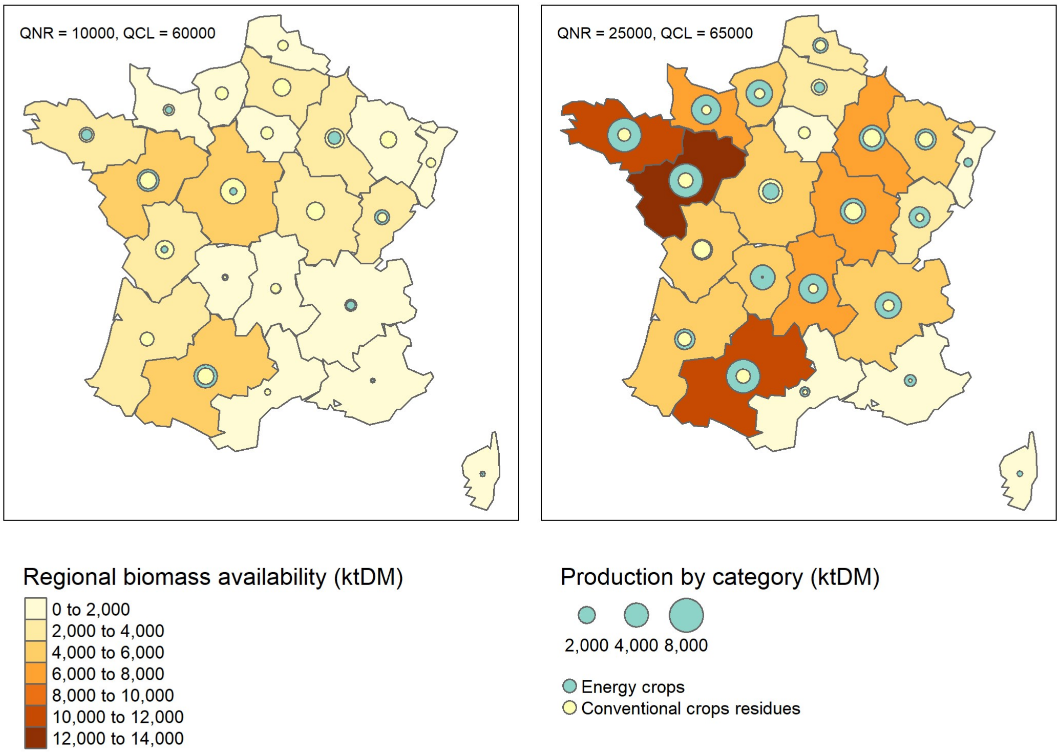

Figure 5. Spatial distribution of potential biomass production in French regions in two contrasted cases: benchmark (left) and maximal bioenergy target reached for a small given increase in food calories (right). The total biomass supply is 44 MtDM in the left panel, of which 15 MtDM of dedicated energy crops and 29 MtDM of residues, and 110 MtDM in the left panel, of which 84 MtDM of dedicated energy crops and 26 MtDM of residues.

system to the demand of new products, namely energy crops. When paired with unconstrained calorie production, the rising bioenergy demand induce gradual and moderate changes in the system: animal capital adjustment does not exceed 8.2% and food crops cultivation also decline steadily, while emissions savings could go up to 12,8 MtCO$_2$eq. Perennial energy crops spread on grasslands, fodders, and land dedicated to various food crops. On the other hand, keeping the calorie production level above its initial value, at 65000 kt$_{sweq}$ for instance, requires more drastic changes in the food production structure when the quantity of bioenergy to be produced increase. As we can see in the bottom right panel of Figure 6, the quantity of livestock collapses because food calories then need to be produced more efficiently, leaving land available for energy crops, and cereal crops cannot be replace as easily because of their calorie content. The discrepancy in N_2O and CH_4 evolution reflects the distortion introduced in the structure of the agricultural food production system through the channel of animal production adjustment because of requirements for productive efficiency and the excessive need for land associated to animal feeding. The savings in agricultural-sourced emissions in the $QCL = 65000$ case range from 0 to 20.5 MtCO$_2$eq depending on the quantity of biomass supplied for biofuels. Let us add that the temporary recovery in CH_4 emissions we can observe in the right panel is traced back to dairy cattle, and mainly driven by milk quotas included in the 2012 version of the model we are using.

For an order of magnitude, the substitution of fossil fuels for advanced biofuels in, for example, road transport, represents in general a 80% reduction in combustion emissions, hence the emission of approximately 2.8 tCO$_2$eq per toe of biofuel incorporated could be avoided (for our 3-to-1 diesel-gasoline ratio). In our model, the potential quantity of biofuels ranges from 13,8 Mtoe (unconstrained optimum) to 40 Mtoe, that is between 38 and 112 MtCO$_2$eq saved emissions. But we should note these estimations do not take into account emissions or pollution related to the

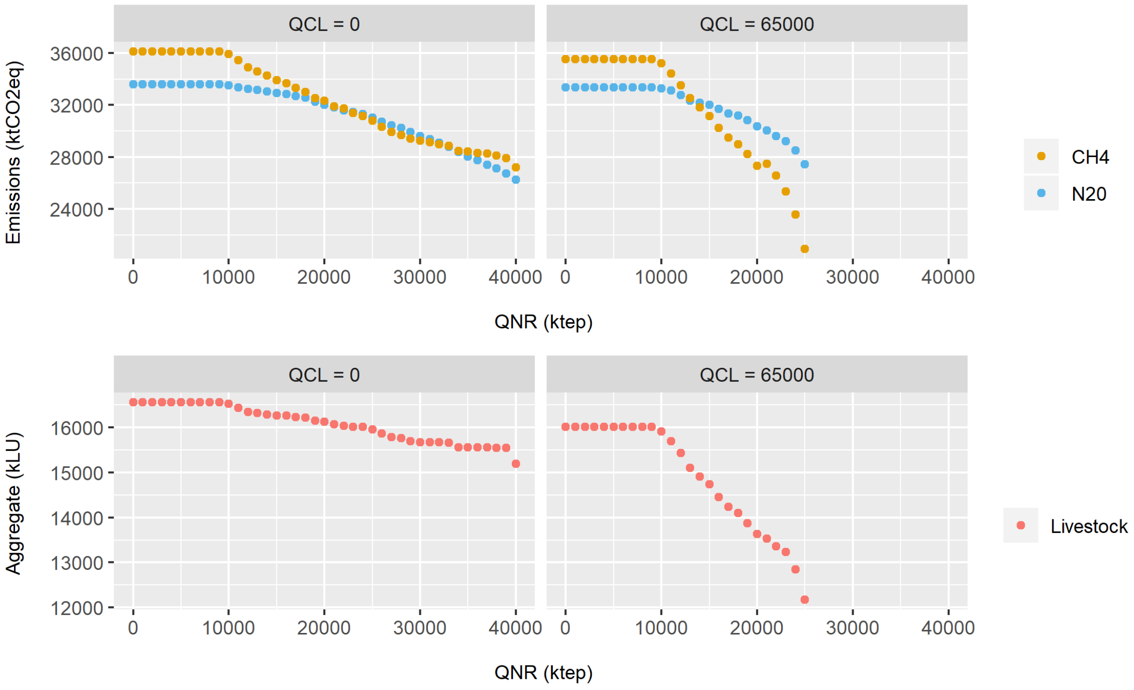

Figure 6. Change in agriculture sourced GHG emissions, differentiating N_2O and CH_4, and in the animal production given QNR, the biofuel quantity to reach, for 2 levels of food calories threshold: 0 and 65000 kt_{sweq}.

transportation of biomass and the transformation processes which could dampen the net carbon footprint of advanced biofuels , but our analysis can help complement life cycle GHG emissions assesments of biofuels, which provide more complete estimates (refer to IRENA (2016)), by including land use change impacts.
Overall, an increase in any of the 2 targets goes together with a significant reduction in greenhouse gases emissions from the production system. This would be mainly due to the saved methane emissions from a lesser livestock production and the introduction of perennial crops with low fertilization requirements supplanting grasslands and conventional crops. Impact on water use should be investigated as perennial grasses yields can show vulnerability to water stress and higher water demand than conventional crops. Soil and water pollution risks however are lower for the energy crops in question (RMT Biomasse Energie (2018)) and the transition from annual crops to energy crops on arable land is found to be at worse neutral, or even to increase the carbon stock in the soil (Don et al. (2012)). The long-lasting impacts on the soil of switching to SRC or herbaceous crops such as miscanthus, and also of the collection of crop residues still need to be further documented. However, the flexible substitution between grasslands and arable lands in the model is a strong assumption, as large effects on carbon storage and biodiversity could be at stake and would need to be taken into account.

4 Concluding remarks

Our analysis shows great potential for France agricultural sector to produce biomass for energy, up to 180 Mt in dry matter, equivalent to 40 Mtoe of biofuels. The production of 110 MtDM of agricultural biomass, that is 25Mtoe of biofuels, shows compatible with a 5% increase in food calories supply. However, advanced processes to transform such lignocellulosic biomass into biofuels still struggles to move to a commercialization phase because of installation and scaling-up costs, and our results are only potentials, discarding the industrial sector of the transformation process, its costs and its structure. We also consider domestic production only and do not include trade in our simulations. Our approach remains prospective and relies on the technical and economical initial conditions implemented in the model. In particular, prices of agricultural products and biofuels are exogenous and constant in our simulations, whereas they would likely evolve under targets and changes of this scale. A significant assumption in a model like ours is the certainty about the existence of a stable market for biomass with a known and guaranteed demand. The risk associated with dedicated biomass production, the lack of information and of established value chains from agricultural production to biorefineries certainly are major barriers for the adoption of advanced biofuels, that are not depicted in our analysis.

Our results highlight complex trade-offs and pervasive changes required in the country's agricultural system to be able to reach ambitious joint targets. When both bioenergy and food calories requirements become challenging, the adjustment variable is the livestock population, as well as animal feed and land allocation to grasslands, at the crossroads of the food production trade-off between foods crops, mostly cereals, and animal production, and the competition for arable land between food crops and energy crops. The growing of energy crops as the need for lignocellulosic biomass increases requires a significant share of land to be diverted from food production and complicates the land allocation choices, even more so for highly productive lands, where great crop potential is found for both cereals and perennial coppices. Facing limited resources, food and bioenergy production have similar coping mechanisms, relying for the most part on a sharp decline in animal production and the displacement of almost all grasslands surfaces, which complicated the simultaneous compliance to both objectives and implies larger changes in the structure of production and in land use than a mere increase in the national food supply. Nevertheless, it seems that reasonable amounts of biofuel produced with lignocellulosic feedstock (up to 10% of the national energy consumption for transports) could be compatible with an increased food calories potential production and moderate and gradual structural changes. This shows that France shows great potential for biomass production for renewable energy, including electricity, heating, and other uses. French biomass resources could be large enough to provide a large scope for action for France, such that, for instance, the promotion of biofuels would not yield a competition with other policy objectives related to agricultural systems such as the use of biomass for methanisation or combustion, which could represent respectively 213 and 42 PJ of primary energy demand from agricultural biomass to meet French targets according to projections (ADEME (2016)). For means of comparison, we find that, in our model unconstrained case, 504 PJ of primary energy in agricultural by-products and 230 PJ in dedicated crops could already be available, and, keeping the level of food calories production, the country's primary energy contained in agricultural biomass could potentially go up to 2 EJ, of which 1.6 EJ from energy crops and 430 PJ from agricultural residues. Note that France indeed has the option to develop the production and use of substantial biomass resources, from both forestry and agriculture, but, while we push our model to the limits of the production set, this essentially shows that there exists a significant margin in which the expansion of bioenergy can be efficiently balanced with other policy goals, food security being one of them, as well as environmental action, through the mitigation of agriculture sourced GHGE and carbon storage in agricultural soil and plants.

We could also say that the introduction of perennial crops in the choice set, subject to a minimum production, pushes the system to switch from profitable activities to producing food calories more efficiently (i.e. displacing animal breeding for the main part), and emit less according to our results, but this might depend on cropping management and intensification and would require life cycle assessments of biofuels emissions reduction, accounting for carbon storage (and potential release when ploughing up grasslands). We only observe environmental outcomes as a result of other constraints and do not account for potentially more effective ways to reduce emissions from agriculture and to target lower emission levels (for example the use of crop residues and by-products for livestock feed instead of energy). Further analysis should also include impacts on water use and irrigation, as well as potential effects of climate change on food and energy crops yield and on the structure of agricultural production.

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