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European farmers' response to crop residue prices and implications for bioenergy policies

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Abstract

To achieve the European bioenergy objectives, member states are likely to implement support policies targeting the use of lignocellulosic biomass for advanced bioenergy. Such policies could increase prices. In this study, we argue that with higher prices and new market opportunities for lignocellulosic biomass, farmers will account for crop residues in their choice of production and use of inputs. We test this hypothesis in an economic model of the EU agricultural supply coupled with a crop model to assess the effect of crop residue prices on residue supply, land allocation, yields, fertiliser use, and nitrogen pollution. We find that 120 million tonnes of dry matter (tDM) of crop residues are co-produced when they are unpriced. The price-induced additional supply is elastic to price but limited to 7% at €100/tDM and 13% at €200/tDM of the unpriced production. However, the increase in residue prices induces farmers to increase their crop areas and yields, which leads to significantly higher fertiliser consumption and nitrous oxide emission. These results indicate to policy makers that supporting prices would not substantially increase crop residue potential but could have collateral effects on the environment. They raise issues of coordination between bioenergy and agri-environmental policies in the EU.

Keywords : Bioenergy, Bioenergy policy, Biomass supply, Crop residues, Mathematical programming model.

JEL Codes : Q18, Q41, Q48, Q53, Q58

1 Introduction

To address climate change, the European Union (EU) intends to move from a fossil fuel-based economy to one based on renewable and carbon-free resources. In particular, the EU has decided to rely on increased use of biological resources. In the energy sector, the 2018/2001 directive sets ambitious, binding targets for the use of renewable energy by member states,¹ while the contribution of bio-based energy to these objectives is expected to be significant (Scarlat, Dallemand, et al. 2019). For transport, the use of bioenergy is even specifically targeted.² More broadly, a *Bioeconomy Strategy* has been adopted by the European commission with the aim of strengthening and scaling-up the bio-based sectors, unlocking investments and markets, and rapidly deploying local bioeconomies across Europe (European Commission 2018). To achieve EU bioenergy targets and initiate the transition towards a bioeconomy, EU member states implement support policies such as feed-in tariffs and premiums, fiscal incentives or subsidies to biomass-processing plants (Banja et al. 2019). Such policies stimulate demand for biomass and are likely to induce a rise in biomass prices. As the environmental provisions of the updated European regulation (notably the 2018/2001 directive) are increasingly incompatible with the use of food and feed biomass for conventional bioenergy,³ lignocellulosic biomass for advanced bioenergy might be especially impacted.

In this study, we argue that higher prices and new market opportunities to sell lignocellulosic biomass would encourage farmers to account for crop residues in their choice of production and use of inputs. In a supply-side model of European agriculture, coupled with a crop model, we integrate crop residues in farmers' economic programme to quantify the economic potential of crop residue supply at the EU level for a range of exogenously given

1. Of the overall Union's energy consumption, 32% must be renewable by 2030, including 14% of the energy used in transport.

2. Advanced biofuels and biogas (i.e. produced from non-food and non-feed biomass) must account for at least 3.5% of the sectoral energy consumption by 2030.

3. Conventional biofuels associated with a high risk of indirect land-use change must be progressively banned from 2023 to 2030, and the share of all conventional biofuels in the energy used in transport must be limited to its 2020 level by member states. In addition, bioenergy must fulfil sustainability and greenhouse gas (GHG) emissions saving criteria to be accounted for in the renewable energy targets that are difficult to reach for conventional bioenergy.

biomass prices. We build crop residue supply curves, analyse how supply responds to rising biomass prices in terms of yields and land use, and discuss the implications of these results for bioenergy policies. We also estimate the impact of higher biomass prices on farmers' use of nitrogen inputs and the associated nitrogen pollution. This leads us to question the compatibility of bioenergy policies with agri-environmental policies. Indeed, by supporting (indirectly) crop residue prices, bioenergy policies might induce a more intensive use of nitrogen fertilisers and generate more nitrogen-related pollution. Conversely, agricultural policies aim to reduce nutrient losses and the use of synthetic fertilisers (Farm-to-fork strategy, European Commission 2020), while environmental policies aim to substantially mitigate GHG emissions, including the significant nitrogen-related GHG emissions from agriculture (Green Deal, European Commission 2019).

Crop residues are a promising feedstock for bioenergy in the EU. They remain largely unexploited and their mobilisation can be achieved without increasing pressure on the environment (Wiesenthal et al. 2006). In particular, the use of crop residues is not expected to cause major land-use changes (Glithero et al. 2013; Scarlat, Fahl, et al. 2019), an aspect on which bioenergy is usually criticised (see for example Searchinger et al. 2008; Beckman et al. 2011; Havlík et al. 2011). Crop residues have a large potential, estimated at between 102 million and 146 million tonnes (t) of dry matter (DM) per year in the EU⁴ (Monforti et al. 2013; Monforti et al. 2015; Scarlat et al. 2010; Scarlat, Fahl, et al. 2019). The amount of crop residues that can be available for bioeconomy, i.e. when the competing uses of crop residues are considered (mainly animal bedding), has also been found to be important. Estimates are between 85 MtDM.year⁻¹ and 133 MtDM.year⁻¹ corresponding to between 36 Mt and 55 Mt of oil equivalent (Monforti et al. 2013; Monforti et al. 2015; Scarlat et al. 2010). By 2030, this amount should be approximately 127 Mt DM (Wietschel et al. 2019).

Thus, the literature indicates that crop residues are and will be a large source of available biomass on which to rely to increase the use of advanced bioenergy and achieve the transition

4. For the EU-27 or EU-28, depending on the studies.

towards a bioeconomy. However, the above-mentioned EU-wide studies are limited to the quantification of a technical potential based on past or projected crop areas and yields. They neither consider crop residue production costs, nor biomass prices in their estimations. In reality, these elements are crucial for quantifying their economic potential.

Several studies deal with the effects of biomass prices on crop residue supply and farmers' economic behaviour. Based on surveys of farmers, Altman et al. (2015), Giannoccaro et al. (2017), and Zuo et al. (2020) show that farmers' willingness to accept, i.e. the minimum price at which they are willing to accept to sell crop residues, is considerably heterogeneous between farmers. Altman et al. (2015) and Giannoccaro et al. (2017) find that the supply of straw is elastic, which means that farmers are sensitive to biomass prices. Zuo et al.'s (2020) results are more contrasting and depend on the type of crop residues. Townsend et al. (2018) also show that the crop residue supply responds to increases in biomass prices; however, they go further to point out that most farmers would adopt, above a certain biomass price, straw management techniques (such as a change in cultivar or an increase in fertiliser use) to increase crop residue yields. These results indicate that biomass prices do not only impact farmers' decision to sell crop residues but also their practices and choice of production. On a wider scale, Chen (2016) uses a multi-market, non-linear, mathematical programming model to quantify the economic potential of crop residue supply in China. He shows that a minimum price of around $\$50.t^{-1}$ is needed to induce Chinese farmers to sell crop residues, and that the supply is extremely inelastic above $\$70.t^{-1}$.

To the best of our knowledge, Chen's (2016) study is the first to use a large-scale agro-economic model to focus on crop residue price and supply. However, no study has yet addressed the effect of crop residue prices on farmers' decision regarding both the crops cultivated and the quantity of inputs applied per hectare (ha). Indeed, in Chen (2016), farmers choose their type of production and decide to collect crop residues depending on whether the price of biomass is above the break-even price of residue collection; however, they do not integrate biomass prices to adjust their input use. In the present study, we

attempt to overcome these limitations. We contribute to the literature by modelling the economic potential of crop residues at the EU level, considering that farmers integrate crop residue prices and yields when choosing their agricultural production and input levels. We rely on the AROPAj agricultural supply-side model coupled with the STICS crop model and integrate the assumed sale of crop residues into the producers' economic programme. This allows us to (i) estimate crop residue supply curves and provide a spatially explicit assessment of the economic potential of biomass supply from crop residues at the EU scale; (ii) analyse the response of biomass supply to price variation at both the intensive (change in crop yields) and extensive (change in crop areas) margins; and (iii) quantify the effect of biomass prices on the level of input use (nitrogen) and input-related pollution.

This study is the first to provide an assessment of the economic potential of crop residues for the EU. For policy makers in the energy sector, our results have important implications regarding the feasibility of the European bioenergy targets and interest and limitations of a direct or indirect (through support for lignocellulosic biomass-processing plants or bioenergy consumption) price-support policy. Our findings are also of interest to a wider audience of policy makers since they highlight potential conflicts between bioenergy, agricultural and environmental policies, and call for a better coordination of EU sectoral policies.

The remainder of the article is organised as follows. In section 2, we introduce the modelling framework and explain how we integrate crop residues into farmers' economic programme. The results are presented in section 3. The methodology and results are discussed in section 4. Section 5 analyses our findings' policy implications.

2 Methodology

2.1 The AROPAj supply-side model

2.1.1 General overview

The AROPAj model is a static, mono-periodic model of the European agricultural supply (Jayet et al. 2021). It comprises a set of independent, mixed-integer linear programming models. Each model describes the production choices - in terms of land allocation, animal and crop production, and inputs used - of a farm that is representative of a group of real farmers. A representative farm, also referred to as a farm group, corresponds to the grouping of at least 15 European farms⁵ individually sampled within the framework of the Farm Accountancy Data Network (FADN). This grouping is conducted at the regional level based on four variables: the technical-economic orientation, economic size, level of irrigation, and altitude of the farm. All the activities identified by the FADN on the farms that constitute a representative farm are represented, except horticulture, viticulture, and market gardening. In the V5-2012 version of the model,⁶ which is the one we use, the European Union has 27 countries (Croatia joined in 2013) and 1993 representative farms.

Each representative farm is assumed to be a price taker, and to choose the level of production and inputs that will allow it to maximise its gross margin under a certain number of technical and institutional constraints. The generic model for representative farm k can thus be written as follows :

$$\left\{ \begin{array}{l} \max_{x_k} \pi_k(x_k) = g_k \cdot x_k \\ s.c. A_k \cdot x_k \leq z_k \\ x_k \geq 0 \end{array} \right. \quad (1)$$

where x_k is a vector of the n production activities for farm k . g_k is a vector of the n gross

5. Minimum number required to ensure compliance with statistical confidentiality.

6. using FADN data for year 2012

margins. A_k is an $m \times n$ matrix associated with the n production activities and m constraints. z_k is a vector of size m that contains the parameters of the constraints.

The activities, x_k , correspond to the areas for crops,⁷ with a distinction made between the production sold and that self-consumed on a farm for animal feed. Vector x_k also contains the production of meat and milk, number of animals in each category (approximately thirty categories of cattle, sheep, goats, pigs, and poultry), and quantity of food purchased. g_k comprises the gross margins associated with each activity and that correspond to the income minus the variable charges, plus the possible payments from the common agricultural policy (CAP). Prices and costs are assumed to be constant, consistent with the price-taker assumption, and are exogenous. The constraints modelled with A_k and z_k are agronomic (crop rotations and animal feed), physical (available land and animal-housing capacity), and regulatory constraints (CAP requirements).

The technical and economic data used in the model are mainly taken from the FADN. These include the variable costs, selling prices, yields, cultivated areas, number of animals, subsidies granted, and farms' technical-economic orientation. Approximately 60,000 European farms from the FADN sample are used to calibrate the model. The calibration process performs a re-estimation of the parameters, which aims to minimise the difference, at the level of the representative farm, between the actual activities observed in the FADN database and the optimal activities that result from the linear programme.

2.1.2 Coupling with the STICS crop model

To represent as accurately as possible the effect of the evolution of the economic context (here, biomass prices) on the agricultural supply, an in-depth description of both the bio-physical processes of agricultural production and farmers' economic behaviour is necessary (Humblot et al. 2017). In the present study, the coupling of AROPAj to the STICS crop simulation model (Brisson et al. 2003) allows for a better representation of farm heterogene-

7. Details of the land use modes modelled are provided in Table 35 of Jayet et al. (2021).

ity by considering soil and climate characteristics and agricultural practices (fertilisation and irrigation) for annual crops. The STICS outputs allow a calibration of yield response functions to nitrogen and water, specific to each representative farm and nine crops.⁸ The yield functions are as follows:

$$y(N, W) = \phi(1 - e^{-\tau(N_0+N)})(1 - e^{-\sigma(W_0+W)}) \quad (2)$$

where y is the actual yield, ϕ is the asymptotic yield, N_0 is the naturally available nitrogen in the soil, N is the amount of nitrogen from fertilisers, W_0 is the natural water supply (rain and soil water), and W is the irrigation water. σ and τ are the curvature parameters associated with water and nitrogen, respectively.

The use of these specific yield functions improves the representation of behaviour as producers can adapt their fertilisation and irrigation practices to physical constraints and market signals (see below, in equation 5, the expression for the gross margin per ha in the maximisation programme). This allows for a fine-grained assessment of the effects of price changes on input demand, yields, and the area allocated to different activities. With these functions, the model is non-linear. To return to the linear formalisation specific to the computer processing developed for the economic model, a two-step procedure is set up. The first step consists of calculating the optimal inputs and yields for each representative farm and crop; the second step uses these calculated data to initialise the optimisation programmes.

2.1.3 Spatialisation

The model's outputs are all spatially distributed on a fine scale via a spatial econometrics method developed by Chakir (2009) that consists in the association of agricultural activities with geo-referenced physical data. This method was applied to the AROPAj model by Cantelaube et al. (2012) and allows us to determine the contribution of the representative

8. In the model, yield functions are available for durum wheat, soft wheat, maize, barley, rapeseed, sunflower, soy, sugar beet, and potatoes. The calibration method used is detailed in Humblot et al. (2017).

farms of a region to the regional agricultural activities on each spatial unit (homogeneous polygons aggregating hundreds or thousands of 100 x 100m pixels).⁹

2.1.4 Nitrogen-related pollution

To quantify the environmental impact of the use of inputs related to crop residue prices, the model accounts for direct nitrous oxide emissions from the use of synthetic fertilisers and indirect nitrous oxide emissions from leaching and atmospheric redeposition, according to the IPCC methodology.¹⁰ Nitrogen pollution in the form of nitrates and ammonia is not assessed here.

2.2 Integration of crop residue into the model

2.2.1 Crop residue yields

Unlike grain yields,¹¹ there are no official data on crop residue yields because crop residues have a low economic value relative to grain output and are seldom traded on commodity markets (Karan and Hamelin 2021; Townsend et al. 2018). The FADN, which is the main source of agricultural data for the AROPAj model, does not provide this information. To overcome this lack of data, we estimate crop residue yields from grain yields using residue-to-product ratios (RPRs). RPRs correspond to the ratios between the residue yield (R) and the grain yield (Y) for a given crop :

$$RPR = \frac{R}{Y} \quad (3)$$

Estimating crop residue yields from RPRs and grain yields is a method widely accepted in the literature (see, for example, Thorenz et al. 2018; Wietschel et al. 2019). Here, we rely on the recent RPR values provided by Thorenz et al. (2018). We consider crop residues for the

9. There are more than 2000 polygons per million hectares, what maintains a high level of resolution.

10. More details on the methodology are available in De Cara et al. (2005)

11. "grain yield", "crop yield" and "main product yield" are used interchangeably in this paper.

following crops: wheat (durum and soft), barley, maize, oat, rye, rice, rapeseed, sunflower, soy, sugar beet, and a group of 'other cereals'¹² (table 1). As yields are on a dry-matter basis in equation (3), the data on grain yields from the FADN are converted using EU standard humidity levels (Eurostat 2020).

2.2.2 Crop residue collection rates

As we are interested in the marketable share of crop residues, we need to know which fraction of the biological production can be sustainably exported from the field and sold. Returning part of the crop residues to the soil is necessary to maintain soil fertility, favour water retention and carbon sequestration, but also to avoid soil erosion. The definition of a sustainable rate of harvesting that both preserves the agro-environmental properties of the soil and maximises the harvesting of residues is complex, as it depends on many factors (soil and climate conditions, cultivation practices, etc.). This issue has been intensively discussed (Bentsen et al. 2014; Ronzon and Piotrowski 2017; Scarlat et al. 2010), and the collection rate values from Scarlat et al. (2010) have been recognised to be a reasonable hypothesis and have often been used (Kalt et al. 2020; Thorenz et al. 2018; Wietschel et al. 2019). We follow the literature and use these values (column 4, table 1).

We can then define a *quantity of marketable crop residues* per ha, $r(y)$, corresponding to the fraction of the residue yield that can be harvested from a technical viewpoint and from an agronomic and environmental sustainability perspective. It is expressed as follows:

$$r(y_{jk}) = \gamma_j \cdot \delta_j \cdot RPR_j \cdot y_{jk} = \alpha_j \cdot y_{jk} \quad (4)$$

with, for crop j , γ_j the sustainable residue collection rate (in % of residue production), δ_j the DM rate of grains and RPR_j the residue-to-product ratio. y_{jk} is the grain yield specific to crop j and the representative farm k .

12. The 'other cereals' category includes different cereal types grouped together because they represent a very small share of the agricultural area. The composition of this category varies between farms. A detailed description of the grouping method is available in table 27 of Jayet et al. (2021).

Table 1: Residue-to-product ratio (RPR), dry matter rate, collection rate and marketable residues for the crops considered in the model.

j -crop	Residue-to-product ratio (RPR_j)	Dry matter rate (δ_j)	Collection rate (γ_j)	Marketable residue factor (α_j)
Barley	0.93	0.86	40	0.32
Maize	1.13	0.86	40	0.39
Oat	1.13	0.86	40	0.39
Rapeseed	1.7	0.91	50	0.77
Rice	1.7	0.86	40	0.59
Rye	1.10	0.87	40	0.38
Soy	1.50	0.86	50	0.65
Sugar beet	0.23	0.2	50	0.02
Sunflower	2.70	0.91	50	1.23
Wheat (soft and durum)	1.00	0.86	40	0.34
Other cereals	1.00	0.86	40	0.34

2.2.3 Integration of crop residue sale into farmers' economic programme

According to the neoclassical theory, farmers behaving rationally should choose their practices to adjust their residue yields until the marginal production cost of residues equals the price of the residues. However, farmers do not generally behave in this manner because of very low prices and rare sales opportunities for crop residues; they rather maximise their profit by accounting only for grain yields and prices. However, under rising biomass prices and new market opportunities (for bioenergy and biomaterials, for instance), we can expect a change in farmers' behaviour. In a survey, Townsend et al. (2018) found that a large proportion of farmers interviewed would adapt to higher biomass prices by using more fertilisers to increase crop residue yields. Here, we consider the level of input use (nitrogen and water) per ha as the single lever for farmers to adjust crop residue production to biomass prices.¹³ We assume that farmers are certain to sell crop residues, i.e. there is no uncertainty about market opportunities, and that they adjust their use of fertilisers according to a perfectly anticipated biomass price. We also assume that residues are sold in swath, to be consistent

13. Both water and nitrogen are considered in the yield functions calibrated from STICS outputs. However, in the rest of the paper, we will focus on nitrogen inputs as they are the factors of production best represented in the model and most likely to be adjusted in the real world.

with Giannoccaro et al. (2017) who reveal farmers' strong preference for this sale method.¹⁴ The crop-specific gross margin per ha that farmers seek to maximise depends now on both grain and residue yields and can be written as follows:¹⁵

$$\pi = p.y(W, N) + q.r(y(W, N)) - c_W.W - c_N.N - c_F \quad (5)$$

where :

- $y(W, N)$ is the yield function with two inputs, water and nitrogen;
- $r(y(W, N))$ is the quantity of marketable crop residues per ha;
- W and N are the amounts of water and nitrogen supplied per ha, respectively; and
- p , q , c_W , c_N and c_F are, respectively, the prices of grains and residues, costs of water and nitrogen, and fixed costs.

The Lagrangian corresponding to the maximisation programme in equation 5 is therefore given by:

$$\mathcal{L} = p.y(W, N) + q.r(y(W, N)) - c_W.W - c_N.N - c_F + \lambda_1.N + \lambda_2.W \quad (6)$$

with λ_1 and λ_2 the Lagrange multipliers associated with the constraints, $N \geq 0$ and $W \geq 0$, respectively.

Inserting relation (4) into relation (6), the necessary first-order optimality conditions according to Karush-Kuhn-Tucker are as follows:

$$\begin{cases} \frac{\partial \mathcal{L}}{\partial N} = \frac{c_N - \lambda_1}{p + \alpha \cdot q} \\ \frac{\partial \mathcal{L}}{\partial W} = \frac{c_W - \lambda_2}{p + \alpha \cdot q} \end{cases} \quad (7)$$

When the sale of crop residues is not included in the farmers' optimisation programme,

14. We therefore do not consider additional harvesting costs, assuming that straws are systematically cut during the grain harvest, whether or not residues are collected and sold.

15. Crop and farm indices do not appear in equation 5 for reasons of readability.

the first-order conditions are $\frac{\partial y}{\partial N} = \frac{c_N - \lambda_1}{p}$ and $\frac{\partial y}{\partial W} = \frac{c_W - \lambda_2}{p}$. Therefore, in our framework, the valorisation of crop residues is similar to an increase in agricultural prices of αq and provides a production incentive. At the intensive margin, the increase in price leads to a decrease in the optimal marginal productivity of nitrogen (and water) and therefore to an intensification of the nitrogen applied per ha (figure 1A). At the extensive margin, the increase in price should increase the cultivated areas for the crops for which residues are marketable through an increase in the gross margin per hectare due to residue valorisation. Figure 1B shows how both intensive and extensive margins contribute to crop residue production at the farm scale. The slopes correspond to the intensive margin effect: for a given crop, the production of crop residues increases through higher yields but the area dedicated to the crop remains constant. The jump corresponds to the extensive margin effect: above a certain price, the crop becomes more profitable than another one and the farmer decides to increase the area dedicated to this crop.

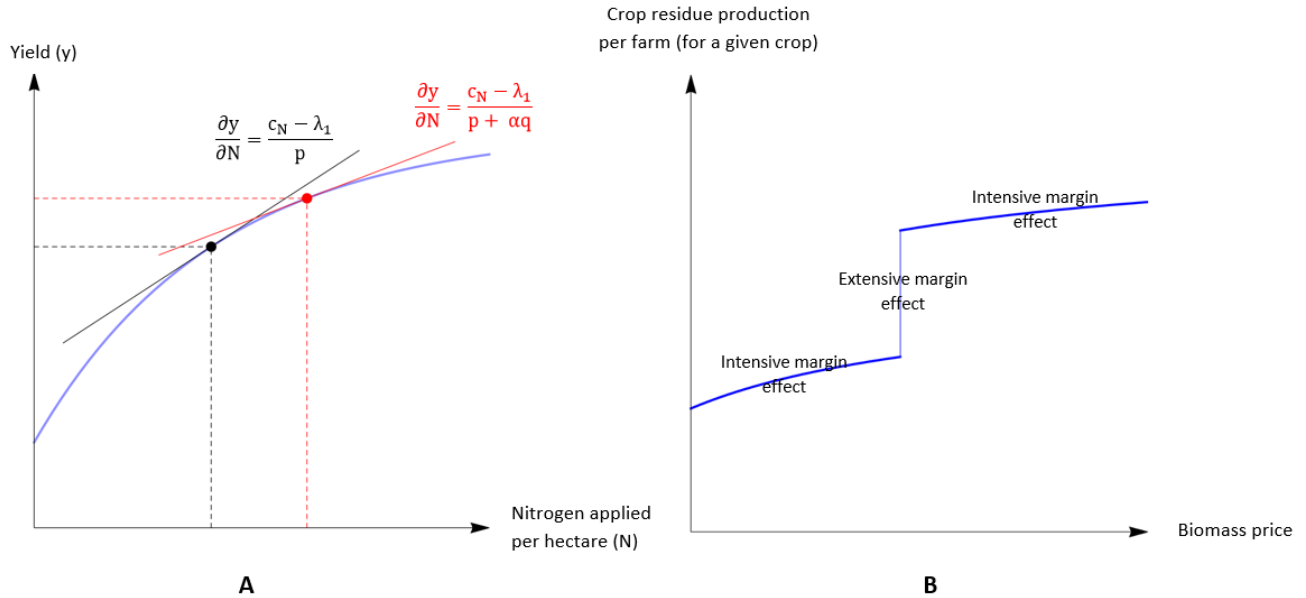


Figure 1: Effect of crop residue prices on the optimal level of nitrogen applied and yield per hectare (A) and on the production of crop residues at the farm scale (B).

3 Results

Simulations are performed for a range of exogenous biomass prices from €2/tDM to 200/tDM, in increments of €2/tDM, under four different scenarios. In the baseline scenario (A), the collection rates for crop residues are those in table 1 while we assume no additional harvesting costs. In scenario B, we consider collection rates that are 15 percentage points lower than in the baseline scenario, and in scenario C, collection rates that are 15 percentage points higher. In scenario D, the collection rates are the same as in scenario A, but additional costs of swathing are assumed at a level of €15/ha (based on Chen (2016) and APCA (2018)).¹⁶ To avoid radical and unrealistic changes in farms' technical-economic orientation due to high biomass prices, we limit the adjustment of the number of animals to +/- 25% in the model compared to the calibration.

3.1 Supply of crop residues

Figure 2 shows the EU-wide aggregate supply of crop residues at various biomass prices under the four scenarios, while figure 3 details the supply of residues for the different crops considered in the model. In our baseline scenario, our analysis indicates that European agriculture could provide between 119 MtDM and 134 MtDM of crop residues, which is consistent with the literature (Monforti et al. 2015; Scarlat, Fahl, et al. 2019). However, this potential is highly dependent on the assumption about collection rates (figure 2). In scenario B, with 15 percentage points (pp) lower collection rates, the supply of crop residues is, on average, 36% lower than in scenario A, between 78 MtDM and 85 MtDM. Conversely, with 15 percentage points higher collection rates (scenario C), the potential supply of residues is, on average, 39% higher and reaches levels between 162 MtDM and 188 MtDM, depending on biomass prices. Additional costs for swathing (scenario D) do not significantly impact the results, and supply curves in scenario A and D almost merge (figure 2). Higher additional

16. We do not test for additional costs per tonne of residues because it is perfectly equivalent to lower crop residue prices in our framework.

harvesting costs would have obviously larger effects on the supply of residues; however, under the assumption of sales in swath, these costs should not substantially exceed the value tested here.

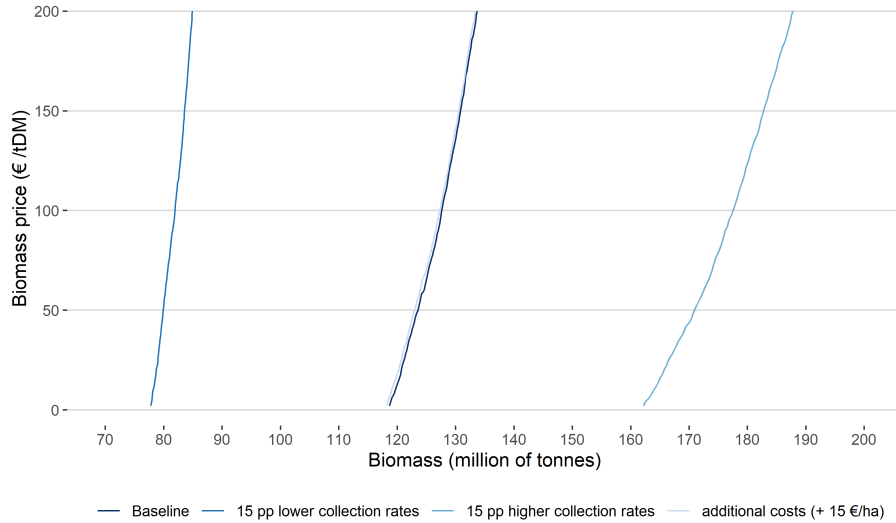


Figure 2: Aggregate crop residue supply curves at the EU level under different assumptions for harvesting costs and collection rates.

In any scenario, at a zero price, a large amount of crop residues is already produced by default as crop co-products. Therefore, it is more appropriate to analyse the effect of biomass prices on the additional supply of crop residues compared to this situation than on the whole supply. In all scenarios and for all crops, the additional supply of crop residues is found to be elastic to price. At the EU aggregate level, the price elasticity of the additional supply, defined as $\frac{\Delta R(p_i)}{R(p_i) - R(p_0)} / \frac{\Delta p_i}{p_i}$ with R the supply of crop residues, p_i the price at the i -th price iteration, and p_0 the reference price (here, €2/tDM), is on average 0.85 for scenarios A,C and D and 0.87 for scenario B. This means that farmers - and thus the additional supply of crop residues - are sensitive to changes in residue prices. However, compared to the quantity of crop residues already co-produced by default, the additional supply of residues due to the increase in prices remains relatively limited. At €100/tDM the additional crop residue supply only represents 7.6% and 7.7% of the default supply in scenario A and D, respectively. For the same biomass price, this additional supply accounts for 5.3% of the default supply

in scenario B and 9.5% in scenario C.

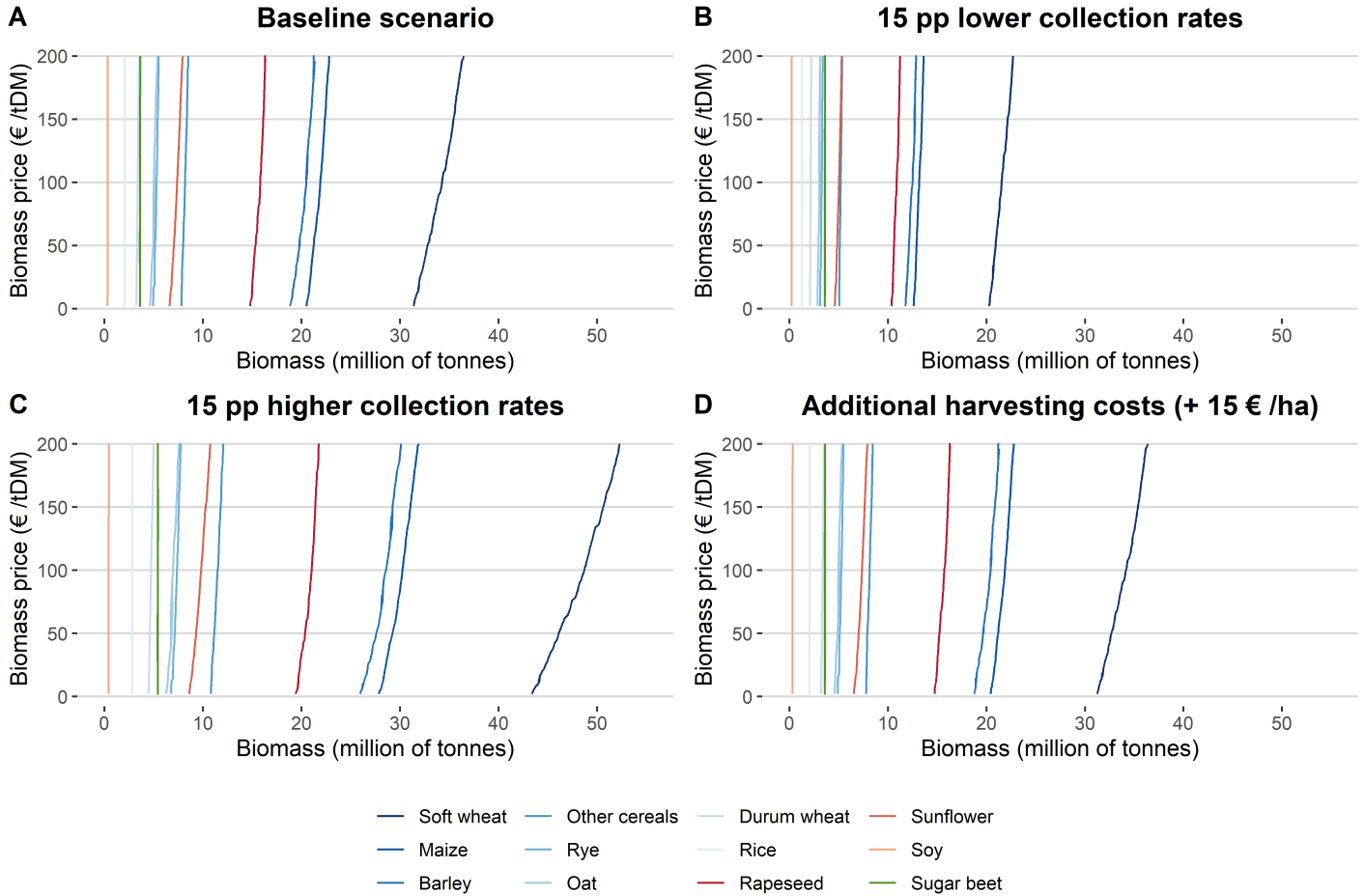
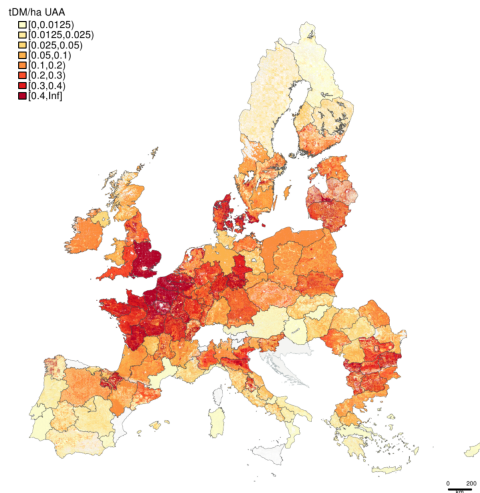


Figure 3: Crop residue supply curves at the EU-level for each crop, under different assumptions for harvesting costs and collection rates.

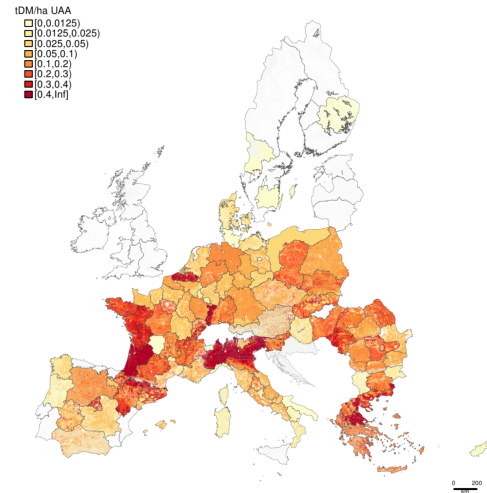
The price elasticities of the additional supply of crop residues that we find are lower than the results in studies based on local farm surveys (0.85 vs approximately 2; Altman et al. 2015; Giannoccaro et al. 2017; Zuo et al. 2020). The differences may be due to our different definition of price elasticity. In these studies, the authors measure the price elasticity of the willingness-to-supply crop residues, while we assess, in this study, the price elasticity of the additional physical production of crop residues, assuming farmers are willing to sell their residues and plan to be paid at a given price for it when they make production choices. Our results are consistent with those in Chen (2016), who finds an inelastic supply of crop residues above the break-even price of residue collection.

In all scenarios, soft wheat, maize, barley and rapeseed are the four main sources of crop residues (figure 3). Wheat straws contribute approximately 27% of the total crop residue supply, while maize, barley and rapeseed residues contribute respectively 17%, 16%, and 12% of this supply. Rice and soy do not provide large amounts of residues because they are secondary agricultural production in the EU (rice and soybean areas represent, respectively, 2.5% and 1.0% of the soft wheat area in the simulations). With a very low RPR and DM rate for residues, sugar beet also offers a limited amount of biomass.

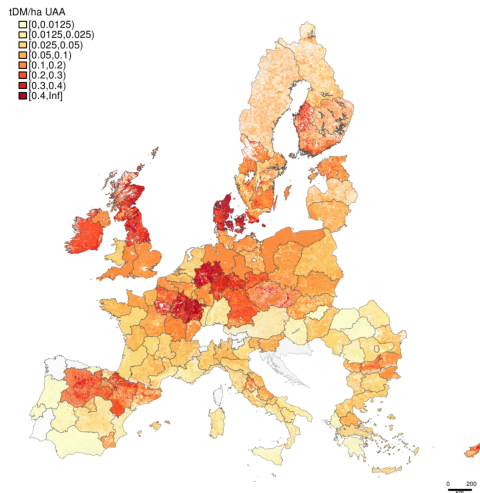
Figure 4 shows the spatial distribution of crop residues in the EU for the five main crops (soft wheat, maize, barley, rapeseed, and sunflower) and the total crop residue production. The supply of crop residues is represented in tDM per ha of utilised agricultural area (UAA) to indicate the extent to which the latter is spatially concentrated, and to eliminate the effect of the regions' sizes. Figure 4a indicates that the northern part of France, south-east of the United Kingdom (UK) and eastern countries of the EU (Bulgaria and Romania) are the preferred locations for the collection of wheat straw. In figure 4b, maize stover is mainly available in western France and in the north of Italy. The potential for barley straw is localised in central Europe, the north of the UK, Ireland, Denmark, and the northern part of Spain (figure 4c). Rapeseed residues are rather concentrated in central Europe while sunflower residues are found in the southern half of the EU, with a particularly high concentration in Romania (figures 4d and 4e). Overall, when all sources of crop residues are considered (figure 4f), we observe that the supply of crop residues is rather evenly distributed across the EU, with the exception of the Iberian Peninsula and northern Scandinavia, that have more limited potentials.



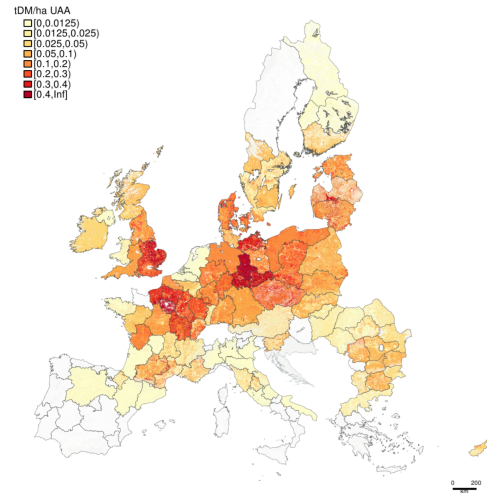
(a) Soft wheat



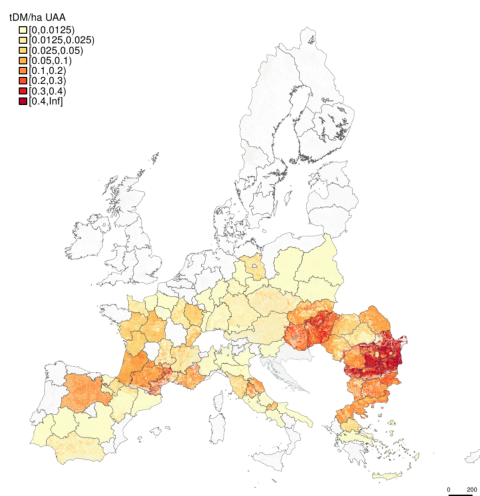
(b) Maize



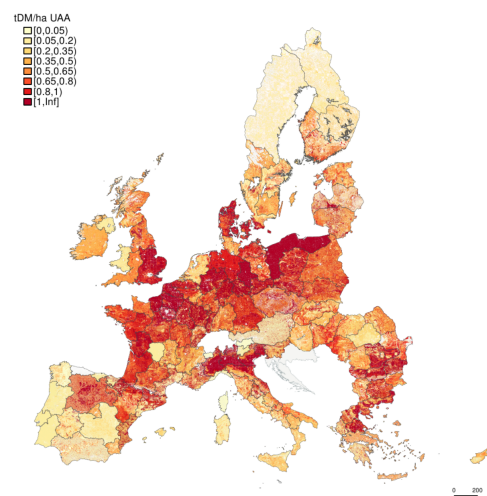
(c) Barley



(d) Rapeseed



(e) Sunflower



(f) Total residues

Figure 4: Spatial distribution of crop residues for the main crops and for all crops at a biomass price of €100/tDM in the baseline scenario.

3.2 Extensive and intensive margin effects

The coupling of the AROPAj model with the STICS crop model allows us to model both the increase in area (extensive margin) and increase in yield (intensive margin) of different crops when biomass prices vary. In figure 5, changes in yields in response to changes in biomass prices are represented. These changes in yields, denoted $\frac{\Delta y_j}{y_j}$, are crop-specific and correspond to relative variations of yields. They are calculated as the means of relative changes in farm groups' yields, weighted by the number of farms in each farm group, and by using yields with a biomass price of €2/tDM as the baseline. This is expressed as follows:

$$\frac{\Delta y_j}{y_j} = \frac{1}{\sum_{k, s_{jk} > 0} N_k} \sum_{k, s_{jk} > 0} \left(\frac{y_{jk}^*(q) - y_{jk}^*(q_0)}{y_{jk}^*(q_0)} \right) \times N_k \times 100$$

where k, j, q and q_0 are, respectively, the index for the farm, index for the crop, biomass price at which the relative yield change is calculated, and the biomass price used as the baseline (€2/tDM). N_k is the number of farms clustered in farm group k , s_{jk} the area of crop j in farm group k and $y_{jk}^*(q)$ the optimal yield for crop j in the farm group k at a crop residue price of q .

In figure 5, the increase in yields in response to biomass prices is steady and monotonous for all crops. Sunflower has the highest increases in yield, reaching 3.5% at a biomass price of €50/tDM and even 7.2% at €100/tDM. Sunflower has an RPR that is more than twice that of major crops, which induces this greater sensitivity of yields to residue prices. Yields for soft wheat, barley, maize and durum wheat are also sensitive to biomass prices. Yields for soft wheat increase by 2.8% at a biomass price of €50/tDM and by 5.4% at €100/tDM. Yields for barley, maize and durum wheat are approximately 1.7-2.1% higher at a price of €50/tDM and 3.4-4.0% higher at €100/tDM. Yield variations are more moderate for soybean and sunflower, and zero for sugar beet. For the latter, crop residues that are marketable account only for 2% of the main product yield (see table 1), which explains the almost zero effect of the residue price on yields. The substantial increases in yields for most crops and the major

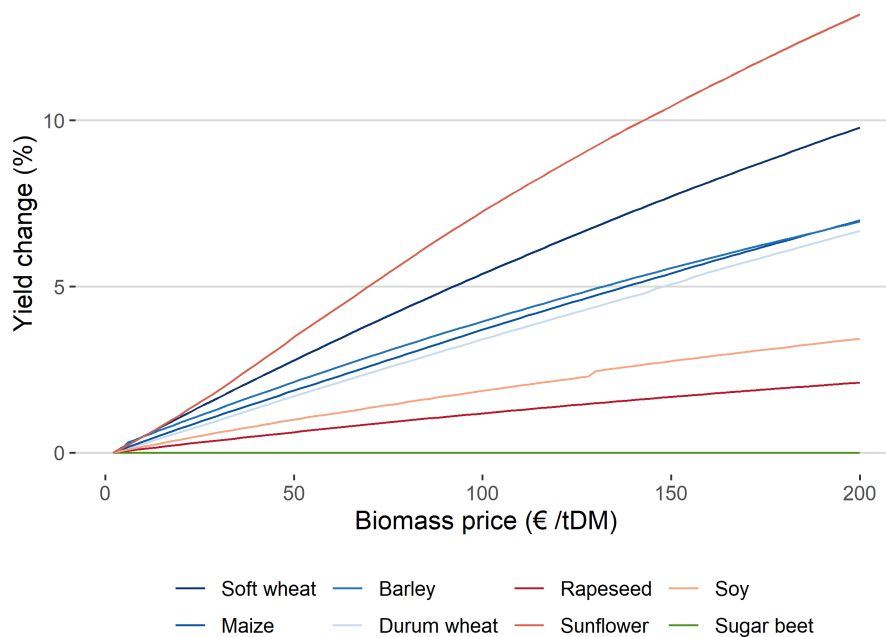


Figure 5: Variation (in %) in crop yields in response to changes in biomass price.

ones indicate an important response of crop residue supply to biomass prices at the intensive margin.

At the extensive margin, higher biomass prices imply changes in the areas for the crops for which residues are marketable. Figure 6 shows that all crops, except durum wheat, rice and sugar beet, show an upward trend with biomass prices at the EU aggregate level. The decreases in area that punctuate the upward trend for a given crop are due to declines in profitability for the crop relative to others in some representative farms when biomass prices increase. The increase in area that follows the decreases is due to a relative increase in profitability for the same crop in other representative farms. The oat area shows the most increase. For this crop, a 6.3% increase in area is reached at a biomass price of €50/tDM and an 8.2% increase at €100/tDM. Rye and rapeseed also show substantial increases in area in response to residue prices, exceeding 10% for high biomass prices. The curve for soy area variations is characterised by jumps, as shown in figure 1B. The jumps, which characterise changes in crop rotation above a certain biomass price at the farm level, are generally

smoothed at the aggregate level; however, in the latter case, the number of representative farms growing soy is too small to obtain smoothing effects.¹⁷ The stability or decrease in area for durum wheat, rice, and sugar beet means that the increase in profitability for these crops with biomass prices is lower than that for other crops.

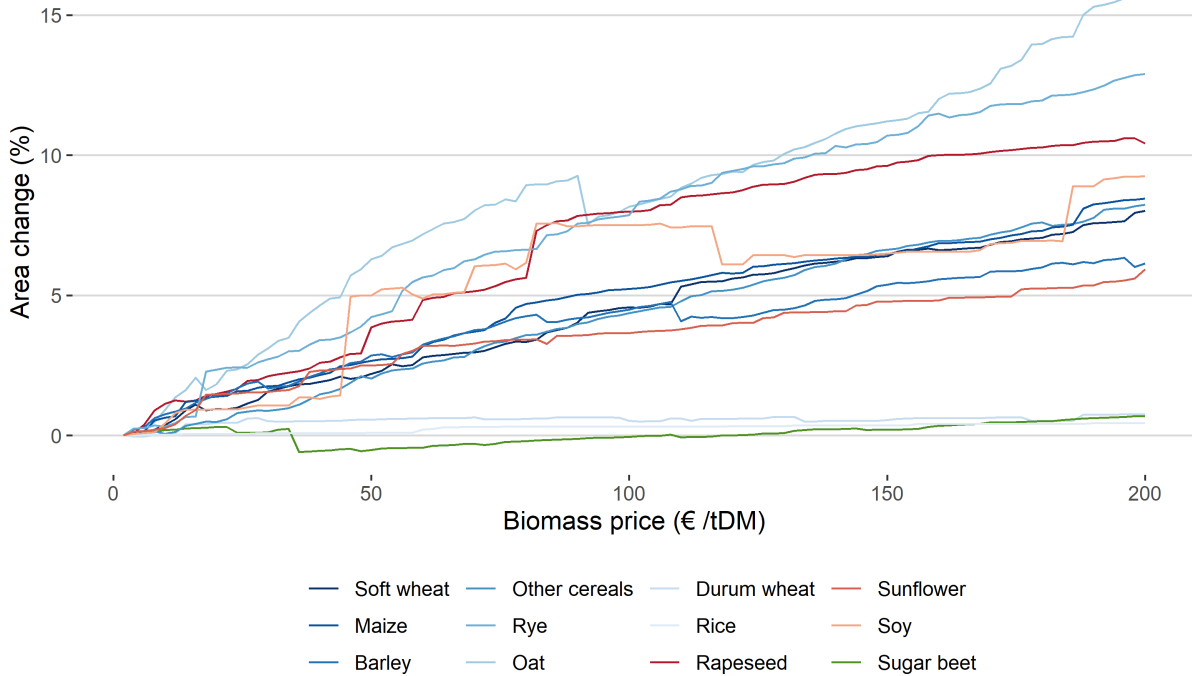


Figure 6: Variation (in %) in crop areas in response to changes in biomass price.

Table 2 shows agricultural land use in the EU in the baseline scenario for biomass prices of €2/tDM, €50/tDM, €100/tDM and €150/tDM. The total area dedicated to crops for which residues are marketable is 72.2 Mha at a biomass price of €2/tDM. At a price of €50/tDM, this area increases by 1.9 Mha, and by 3.5 Mha at €100/tDM. The expansion in these crops with rising residue prices is compensated for by an intensification of the ruminant livestock sector through a switch from grass-based to maize-forage and concentrate-based systems, and to a lower extent by a reduction in the number of ruminants. When the price of crop residues rises from €2/tDM to €100/tDM, the grassland area decreases by 4.2 Mha while maize forage

17. Approximately 130 representative farms grow soybeans in our simulations

gains 0.3 Mha and the self-consumption of cereal grains as concentrate on animal farms rises by 2.0 Mt.¹⁸ This contributes to a decrease in the total forage area by 4.1 Mha and to an 8% increase in stocking rate to 1.70 livestock units (LUs)¹⁹ per hectare. The number of ruminants remains relatively stable, decreasing by 1.3% or 0.9 MLUs. Intensification of the ruminant feeding systems contributes 85% of the total forage area spared while the reduction in the number of animals contributes only 15%. A part of the agricultural area that is spared through the changes in the ruminant livestock sector is not dedicated to crops for which residues are marketable but is converted to fallow land.

Thus, observations of crop yield and area variations indicate that extensive and intensive margins are both key components of the response of crop residue supply to rising biomass prices. At a biomass price of €100/tDM, both yields and areas increase by between 5% and 10% for the main crops. The increase in crop area results largely from the conversion of grasslands and intensification of ruminant systems. Such response of the agricultural sector to rising biomass prices seems to be beneficial for the energy sector and achievement of EU bioenergy targets. However, it raises environmental issues insofar as putting new land under cultivation and increasing yields to produce more biomass necessarily requires increased use of nitrogen fertilisers that will generate more nutrient losses to soil, air, and water. The next subsection addresses this issue and quantifies the effect of rising biomass prices on the use of nitrogen inputs and nitrogen pollution.

3.3 Use of nitrogen fertilisers and nitrogen pollution

Figure 7 shows the effect of an increase in crop residue prices on the use of nitrogen fertilisers and nitrous oxide emissions at the European level. Both the consumption of nitrogen fer-

18. The number of pigs and poultry remains constant; thus, we are certain that the increase in the self-consumption of grains is for ruminant feed.

19. The conversion of the number of animals in LU relies on the following figures from Eurostat : 1 bovine animal under 1 year old (yo) = 0.4 LU ; 1 bovine animal between 1 and 2 yo = 0.7 LU ; 1 male bovine animal, 2 yo and over = 1 LU; 1 heifer, 2 yo and over = 0.8 LU; 1 dairy cow = 1 LU; Other cow, 2 yo and over = 0.8 LU; 1 sheep = 0.1 LU ; and 1 goat = 0.1 LU.

Table 2: Land use at the EU level for a set of biomass prices under the baseline scenario.

	Biomass price (€/tDM)			
	2	50	100	150
Area of crops with marketable crop residues (Mha)				
Soft wheat	19.7	20.2	20.6	21.0
Maize	8.1	8.3	8.5	8.6
Barley	14.7	15.1	15.3	15.5
Other cereals	5.8	5.9	6.1	6.2
Rye	3.2	3.3	3.4	3.5
Oat	3.7	3.9	4.0	4.1
Durum wheat	2.9	2.9	2.9	2.9
Rice	0.5	0.5	0.5	0.5
Rapeseed	6.2	6.5	6.7	6.8
Sunflower	3.9	4.0	4.0	4.0
Soy	0.2	0.2	0.2	0.2
Sugar beet	3.3	3.3	3.3	3.3
Total	72.2	74.1	75.7	76.7
Area of fodder crops for ruminant feed (Mha)				
Grasslands	29.9	27.6	25.7	23.8
Maize forage	4.6	4.7	4.9	4.8
All forage	47.0	44.7	42.9	40.9
Number of ruminants (MLUs)	73.9	73.3	73.0	72.6
Stocking rate (LU/ha of forage)	1.57	1.64	1.70	1.77

tilisers and the resulting nitrous oxide emissions monotonously and regularly increase with crop residue prices. At a price of €100/tDM, the overall consumption of fertilisers is 42.8 Mt, 14.9% more than in the situation in which biomass is sold at €2/tDM. N₂O emissions follow the same trend. Direct N₂O emissions from fertilisers increase by 16.1%, indirect N₂O emissions from leaching by 7.9%, and indirect N₂O emissions from atmospheric redeposition by 4.8%. This represents an overall increase in agricultural GHG emissions of 7.9 MtCO_{2eq}, or 1.7% of the EU agricultural emissions (estimated at 463 MtCO_{2eq} by the European Environment Agency for the year 2019).

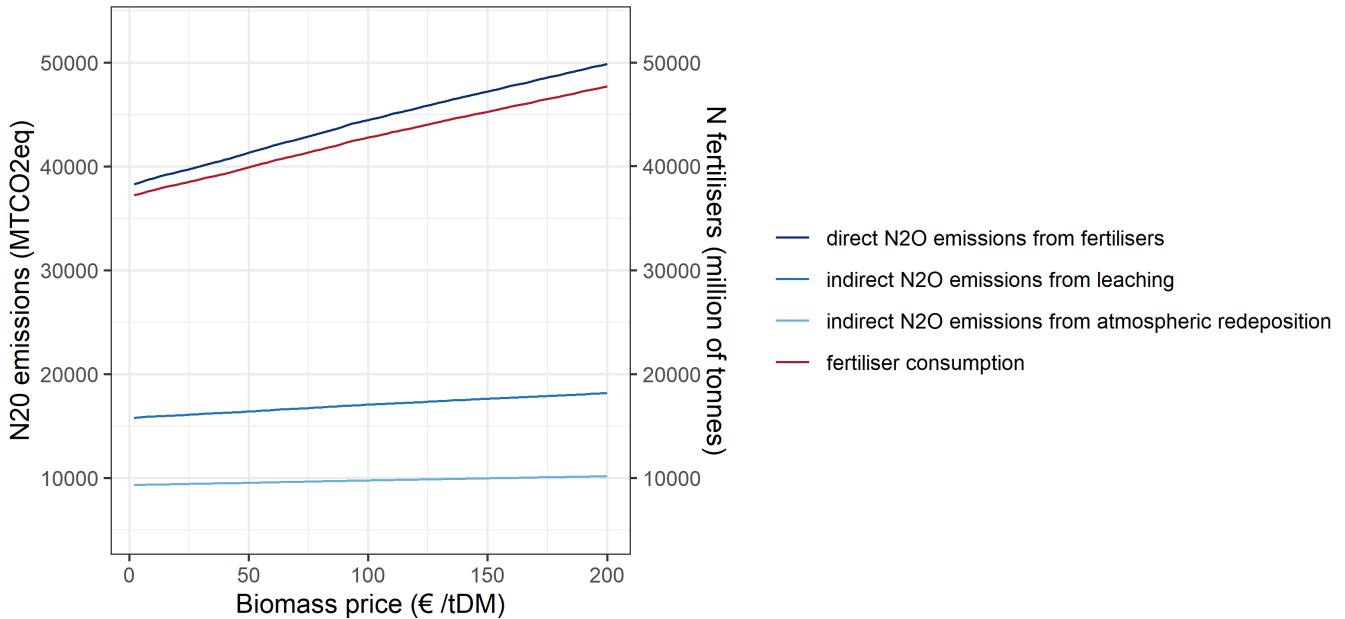


Figure 7: Use of nitrogen fertilisers and nitrous oxide emissions for different biomass prices at the EU aggregate level.

Thus, the simulations indicate that higher crop residue prices -which could result from a policy that supported the bioenergy sector to achieve the EU targets- would result in a substantial increase in the consumption of nitrogen fertilisers and nitrogen losses in the form of nitrous oxide. This obviously raises environmental issues: it also questions the potential incompatibilities between energy, agricultural and environmental European policies. Some perspectives and policy implications of these results are discussed in the following sections.

4 Discussion

4.1 Discussion of the methodology and assumptions

Due to a lack of data, we estimate residue yields using a method that is based on RPRs and relies on constant and crop-specific RPR values that are available in the literature (Thorenz et al. 2018). This assumption of constant RPRs has been criticised in the agronomic literature. Several studies have estimated RPRs through meta-analysis of field measurements of crop residue and grain yields and shown that the RPRs is likely to be a decreasing function of the yield (Bentsen et al. 2014; García-Condado et al. 2019; Ronzon and Piotrowski 2017; Scarlat et al. 2010). Given that the RPR values we have chosen are equivalent to average RPRs, we probably underestimate RPRs for low grain yields and overestimate them for high grain yields in this paper. However, Karan and Hamelin (2021) show that the current RPR functions available in the literature give significantly different estimates of crop residue yields and therefore the choice of the function would have introduced a bias in our simulations. In addition, the estimated RPR functions are non-linear (Bentsen et al. 2014; García-Condado et al. 2019; Ronzon and Piotrowski 2017; Scarlat et al. 2010) and it would have been much more complex to incorporate them into the farmers' economic programme.

Alternative uses of crop residues on farms (especially for animal bedding) are not considered in the model. However, the current use of crop residues by farmers changes the opportunity cost for farmers to sell crop residues to the market and therefore their willingness to sell (Lynes et al. 2016; Zuo et al. 2020). Further research that considers different opportunity costs, by adding, for instance, a constraint on the residues required for animal bedding in the optimisation process for livestock farms, is required. Not accounting for this heterogeneity leads to somewhat overestimate the economic potential of crop residues sold in swath in this study, particularly when biomass prices are low and below the opportunity cost of residues for most farms. Additionally, we do not consider the unwillingness of farmers to sell crop residues because of their aversion to the risk of loss of soil organic matter,

and fertility degradation due to residue collection (although we use collection rates that are not supposed to induce soil degradation). This is another source of overestimation of the economic potential assessed in this paper.

Our results rely on the assumption that residues at field will be collected by the buyer. This may be questioned, although there are several elements that show this assumption to be reasonable. It is not unusual for farmers to buy standing grass and harvest it themselves, and we can imagine that with a developed bioeconomy, companies specialised in the collection and transport of biomass could emerge and provide services at low cost (efficiency gains of equipment and economies of scale). This option might also be preferred by farmers because it would be timesaving and would not require additional investment in specific equipment for residue collection, as underlined in Glithero et al.'s (2013) study. This is further supported by Giannoccaro et al. (2017), who indicate that the preferred method of selling cereal straws in their experiment is in swath.

We do not consider the possibility of farmers' changing the cultivar to a higher residue-yielding one, although it is one of the main crop management adjustments envisaged by farmers when considering an increase in residue prices (Townsend et al. 2018). However, cultivars with higher residue yields have generally lower grain yields, which implies a trade-off between the two outputs (Townsend et al. 2017). Given the relative prices of residues and grains, the adoption of a high residue-yielding cultivar is unlikely to be economically preferable for farmers.

Finally, as a supply-side model, AROPAj considers prices as exogenous data and does not consider their reaction to variations in production. In our simulations, an increase in biomass prices induces an increase in the production of both grains and residues at the EU scale. The additional production of grains should negatively impact the market price for grains, p , and reduce the incentive to grow crops for which residues are marketable at both extensive and intensive margins²⁰. Therefore, the response of crop residue supply to rising biomass prices

20. In an equilibrium model, $p + \alpha q$ would be lower and the optimal marginal productivity of nitrogen higher (see equation 7), leading to a less intensive use of nitrogen fertilisers and lower yields.

is likely to be slightly overestimated in this supply-side approach.

4.2 Discussion of the results

Our results indicate that the European agricultural sector could already provide 123 Mt of biomass from crop residues with no change in production and an *a priori* limited impact on soil quality. Thus, crop residues might be a key feedstock for bioenergy and the bioeconomy. However, this potential remains theoretical at this stage as there is almost no demand for crop residues in the EU energy sector (Scarlat et al. 2010). Very few ligno-cellulosic biomass-processing plants exist, with no economic agent specialised in the logistics of biomass flows (collection and transport) on a large scale. Public action should therefore focus on developing and supporting the downstream part of the biomass-processing chain to mobilise the current crop residue potential.

While the additional supply of crop residues is elastic to price, it remains limited in quantity compared to the crop residues already co-produced by default (when they are unpriced). At €100/tDM, the additional production of crop residues corresponds to only 7.7 % of the default supply of residues. For policymakers, this shows that the achievement of renewable energy and bioenergy targets should not rely on a large increase in crop residue supply due to price effects and new market opportunities, because this increase is likely to be very limited. While a policy that guarantees a minimum purchase price to producers for crop residues could be useful in unlocking their unwillingness to sell (as shown by Altman et al. 2015; Giannoccaro et al. 2017; Townsend et al. 2018; Zuo et al. 2020)) and mobilising the existing co-production of crop residues, such policy would be rather inefficient in substantially increasing this production. In addition to the price issue, attention should be paid to the type of contract offered to farmers for residue collection (Glithero et al. 2013). For investors, the results indicate the size of the potential market and can guide the sizing of industrial equipment.

When we decompose the response of crop residue supply to biomass prices between the

extensive and intensive margins, we find that in the range of simulated prices, both significantly contribute to the rise in supply and both areas and yields increase in the order of 5 to 15%. At the extensive margin, the increase in crop areas occurs at the expense of permanent grasslands. This raises issues of GHG emissions related to carbon removal from grassland soils as well as of nitrogen losses due to the reduction of permanent soil cover that normally contributes to nitrogen retention. At the intensive margin, the increase in yields results from an increased use of synthetic nitrogen fertilisers and leads to higher nitrous oxide emissions, and probably to higher nitrate and ammonia losses in water, soil, and air, although the latter are not quantified here. When biomass prices rise from €2/tDM to €100/tDM, the production of crop residues increases by 7.7% vs 12.2% and 13.4% for fertilisers and direct nitrous oxide emissions, respectively, which questions the cost-benefit ratio. Beyond the environmental concerns, these findings highlight potential conflicts between the EU bioenergy policy with the Farm-to-Fork strategy that aims to reduce the use of nitrogen fertilisers by 20% and nitrogen losses by 50% (European Commission 2020), and the Green Deal that targets a 55% reduction in emissions by 2030 in the EU (European Commission 2019). Our results clearly call for a better coordination of energy, agricultural and environmental policies. A possibility would be to simultaneously implement a guaranteed minimum purchase price to unlock farmers' reluctance to sell their residues and a tax on nitrogen inputs to limit the economic incentive to intensify. This idea should be understood from the perspective of limiting the negative collateral effect of a biomass price-support policy on the environment. Another option to stimulate the supply of ligno-cellulosic biomass would be to rather promote perennial energy crops such as Miscanthus instead of crop residues. Indeed, perennial crops could partially replace permanent grasslands as in our results, but without inducing substantial removal of soil organic carbon since they offer a permanent soil cover and do not imply a conversion to annual crops. In addition, perennial energy crops do not require a large amount of nitrogen fertilisers, and mixed policies that combine a support for such crops with a tax on nitrogen inputs have been found to achieve significant cost-effectiveness gains

for the abatement of nitrogen losses (Bourgeois et al. 2014).

5 Conclusion and policy implications

To achieve the bioenergy targets set by the RED II, as well as to accelerate the desired transition to a bioeconomy, the EU or its member states will have to stimulate the biomass sector by support policies. This may include a guaranteed minimum purchase price for biomass producers such as feed-in tariffs or premiums and support for biomass-processing plants or bioenergy consumption. In all cases, interventions should lead directly or indirectly to a rise in biomass prices, specifically ligno-cellulosic biomass, and send a market signal to producers. In this study, we attempt to quantify how biomass prices would impact the supply of crop residues and the agricultural sector, arguing that farmers would integrate crop residues in their production choice if biomass prices rose. We show that the supply of crop residues is important even when crop residues are not valorised, and that the price-induced additional supply of residues is elastic to price. However, this additional supply is limited compared to the already existing crop residue co-production. These results suggests that policy makers should not rely on an important additional production of crop residues with higher prices to meet the policy targets, but should rather focus their efforts on mobilising the existing potential.

The effect of prices on crop residue supply implies variations in both crop areas and yields. For crops for which residues are marketable, areas increase mainly at the expense of permanent grasslands while yields increase through a more intensive use of nitrogen fertilisers. These changes moderately impact the supply of residues but raise environmental concerns regarding the potential rise in the use of nitrogen fertilisers, nitrogen losses, and nitrous oxide emissions. These findings call for a better integration and coordination of energy policies with agricultural and environmental policies, especially the Farm-to-Fork strategy and Green Deal that, conversely, aim to reduce the use of fertilisers, nutrient losses, and GHG emissions.

The question of the choice of instruments to be implemented to limit conflicts between these sectoral policies remains open. Based on the literature and on economic theory, we propose here to combine a tax on nitrogen inputs to a hypothetical support policy for the bioenergy sector or to focus public support on other sources of lignocellulosic biomass such as perennial crops.

Other important questions related to crop residue supply, bioenergy, agriculture and the environment should be addressed in future research. In our study, we do not assess the effect of prices on farmers' collection rates, which we assume constant. However, with very high biomass prices, farmers might be incentivised to collect more residues at the expense of soil quality and fertility. The different opportunity costs of residues because of different alternative uses (notably for animal bedding) may induce large differences in farmers' willingness-to-supply as shown by Zuo et al. (2020), resulting in heterogeneous, spatial distribution of residue supply depending on the regional agricultural specialisation. This should have important implications for investors regarding the location of future biomass-processing plants, and for policy makers regarding local energy-supply strategies. From a longer-term perspective, agricultural and food orientations could provide more residues. The shift towards less meat-based diets is expected to reduce the demand for crop residues for animal bedding while the development of organic agriculture, characterised by lower yields and larger areas, might increase the global RPRs. This is another avenue to be considered.

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