Potential trade-offs of employing perennial biomass crops for the bioeconomy in the EU by 2050: Impacts on agricultural markets in the EU and the world

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Abstract

Perennial biomass crops (PBC) are considered a crucial feedstock for sustainable biomass supply to the bioeconomy that compete less with food production compared to traditional crops. However, large-scale development of PBC as a means to reach greenhouse gas (GHG) mitigation targets would require not only the production on land previously not used for agriculture, but also the use of land that is currently used for agricultural production. This study aims to evaluate agricultural market impacts with biomass demand for food, feed, and PBC in four bioeconomy scenarios (“Business as usual,” “Improved relevance of bioeconomy,” “Extensive transformation to a bioeconomy,” “Extensive transformation to a bioeconomy with diet change”) to achieve a 75% GHG reduction target in the emission trading sector of the EU until 2050. We simulated bioeconomy scenarios in the energy system model TIMES-PanEU and the agricultural sector model ESIM and conducted a sensitivity analysis considering crop yields, PBC yields, and land use options of PBC. Our results show that all bioeconomy scenarios except the one with diet change lead to increasing food prices (the average food price index increases by about 11% in the EU and 2.5%–3.0% in world markets). A combination of the transformation to a bioeconomy combined with diet change toward less animal protein in the EU is the only scenario that results in only moderately increasing food prices within the EU (+3.0%) and even falling global food prices (−6.4%). In addition, crop yield improvement and cultivation of PBC on marginal land help to reduce increases in food prices, but higher land prices are inevitable because those measures have only small effects on sparing agricultural land for PBC. For a transition to a bioeconomy that acknowledges climate mitigation targets, counter-measures for those substantial direct and indirect impacts on agricultural markets should be taken into account.

Keywords
bioeconomy, food security, greenhouse gas mitigation, lignocellulose biomass, nexus, perennial biomass crops
1 | INTRODUCTION

The EU-bioeconomy strategy has been put forward to contribute to a low-carbon and resource-efficient economy in order to address societal challenges such as climate change mitigation, resource depletion, and sustainable economic growth (EC, 2012). The use of biomass resources in such a bioeconomy should focus on high value-added and resource use efficiency (Figure 1). For example, the biomass-to-energy processes currently used require high volumes of biomass and produce only low-value outputs. In contrast, biomass-to-biochemical/material processes would yield higher value outputs, for example, pharmaceuticals, polymers, lubricants, or bioplastics; functional materials with relatively small demand for biomass. Many of those new biochemical/material products emerge in the market due to their superior quality in strength, toxicity, and sustainability compared to fossil-based ones (Rönnlund et al., 2014). An overall increase in the efficiency of biomass use in the bioeconomy can be achieved by promoting the cascading use of biomass (Figure 1). However, a key question for the bioeconomy is how much biomass resources can sustainably be harnessed from agriculture while ensuring food security (Scarlat, Dallemann, Monforti-Ferrario, & Nita, 2015).

In 2013, bioenergy supplied 4.5 EJ (10%) of final energy consumption. This being mostly for heat (75%), followed by electricity (13%) and transport (12%) (EC, 2017). In 2012, approximately 5.5 Mha of arable land (3.1% of the utilized agricultural area (UAA)\(^1\)) was utilized to grow feedstock for bioenergy (EC, 2017). Food-based first-generation (1G) biofuels have been criticized not only for their low resource use efficiency, but also their contribution to increases in food prices (ECOFYS, 2014; Popp, Lakner, Harangi-Rákos, & Fári, 2014; Zilberman, Hochman, Rajagopal, Sexton, & Timilsina, 2013). In addition, there is uncertainty about their actual GHG mitigation effects due to potential GHG leakage via indirect land use change (iLUC) (Laborde, 2011; Searchinger et al., 2008; Valin et al., 2015). Depending on the reference land system (Koponen, Soimakallio, Kline, Cowie, & Brandão, 2018) and biomass origin (Richard et al., 2018), the GHG mitigation effect of bioenergy varies significantly. It is necessary to increase biomass use efficiency while ensuring food security and its actual environmental effects in GHG mitigation.

Meanwhile, perennial biomass crops (PBC), such as perennial grasses and short-rotation coppices, have emerged as an alternative source of biomass (2nd generation, 2G) because of their nonfood nature (i.e., lignocellulosic biomass) and lower environmental impacts due to higher land productivity and fewer input requirements as compared to conventional crops (Valentine et al., 2012; Wagner & Lewandowski, 2016). Thus, the vision of the bioeconomy with PBC promises efficient, sustainable, and renewable biomass supply systems. On the other hand, the sustainability and viability of PBC within agricultural systems are still questionable. Land use competition, especially, is a yet unsolved problem for PBC cultivation in the EU. Marginal land, which is low in productivity and thus often not used for food production, but potentially suitable for PBC cultivation, is considered small (1.35 Mha) in the EU (Allen et al., 2014). Furthermore, land use for PBC would increase land use competition among food crops and PBC, as the demand for the latter grows due to societal needs for the bioeconomy. Thus, it may influence food prices in the same way, though to a lesser extent, as 1G biofuels do.

Besides PBC from agriculture, forestry biomass is generally considered to have the potential to deliver substantial amounts of biomass for the bioeconomy. In addition to that, a lot of biomass is harvested by pruning of hedgerows and activities to reduce forest succession in the context of nature conservation activities. However, the potential of using this nonagricultural biomass as a resource for the bioeconomy is limited. Now, it has already become difficult to satisfy the demand for forest-borne biomass that is used as construction material, paper, and heating. Further increasing the extraction of biomass from forests can be restricted in the short term due to nature conservation considerations and its contradiction to sustainable forest management approaches. Therefore, PBC from agricultural land remain an important biomass resource for the bioeconomy (WBAE & WBW, 2016). Furthermore, long-term biomass supply and demand for GHG mitigation face high uncertainty. From the supply side, biomass potential from agriculture varies according to land availability, human diet changes, and biomass yields (Choi & Entenmann, 2019; Creutzig et al., 2015; Erb, Haberl, & Plutzar, 2012). From the demand side, technical progress in biomass processing technology and its competing technologies in energy systems will determine the level of biomass

\(^1\)According to Eurostat, UAA in the EU is 175.0 Mha in 2013.
demand in the respective sectors, for example, power, transportation, and heat. Thus, energy system models project the share of bioenergy in final energy consumption with high uncertainty due to different assumptions on biomass potential and technical maturity (Rose et al., 2014; Szarka, Eichhorn, Kittler, Bezama, & Thrän, 2016). A holistic approach is therefore necessary, considering energy, agriculture, and land markets to address multiple dimensions of the bioeconomy development. In this context, Climate-Energy-Food-Land-Nexus (Liu et al., 2018) analyses become indispensable.

Previous assessments dealt with those uncertainties about future biomass supply by using biomass potential analysis (Elbersen, Startisky, Hengeveld, Schelhass, & Naeff, 2012; IRENA, 2014; Ruiz et al., 2015). By analyzing only such areas that are currently not under agricultural production (“food first principle”), those studies tried to factor out impacts on food security. They also assumed that rising crop yields would free-up large areas of surplus land in the future on which biomass can be produced without increasing food prices. On the other hand, several studies (Fischer, Hizsnyik, Prieler, Shah, & Velthuizen, 2009; Havlík et al., 2011; Lotze-Campen et al., 2014; Popp et al., 2011) show increases in food prices due to additional land demand for bioenergy. They analyzed PBC development for energy uses for climate change mitigation targets in agricultural sector models. Lotze-Campen et al. (2014) point out that marginal land availability and the yield of PBC on cropland and pasture are critical factors for determining agricultural market impacts. Additionally, coupled model frameworks of agricultural and energy system models attempted to deal with interactions between the energy and agricultural sector with regards to bioenergy (Deppermann, Blesl, Boysen, Grethe, & Bruchof, 2016; Elobeid et al., 2013). However, there are no studies for the EU (Table 1) which take account of explicit PBC supply in a coupled model framework until 2050.

Despite the need to consider direct land use changes of existing cropland and pasture areas due to PBC deployment, to our knowledge, there has been no attempt to explicitly model the substitution effects between PBC and traditional crops/pasture in previous assessments. Modeling PBC in agricultural sector models has often been implicitly handled because of its novelty to farmers and markets (Fischer et al., 2009; Havlík et al., 2011; Popp et al., 2011; Lotze-Campen et al., 2014). Furthermore, PBC shares in total agricultural land have been exogenously given to assess its impacts on agriculture (Becker, Adenäuer, & Fonseca, 2010; Deppermann et al., 2016). Alexander, Moran, Rownsevell, and Smith (2013) modeled PBC growth as spatial diffusion in agent-based modeling, considering contingent interactions between farmers and biorefinery plant investors, where they show that through considering these factors, less PBC cultivation area is seen than in previous studies.

| Studies                        | Scenarios (GHG mitigation targets) | Biomass demand (EJ) | PBC area (Mha) | Modeling systems                                      |
|-------------------------------|-----------------------------------|---------------------|----------------|------------------------------------------------------|
| Forsell et al. (2016)         | −80% in 2050 compared to 1990     | 15.2                | n.a.           | GLOBIOM ← Exogenous demand from PRIMES              |
| Ruiz et al. (2015)            | −80% in 2050 compared to 1990     | 4.8~9.6             | 2.7~9.9        | CAPRI → JRC-EU-Times                                 |
| Deppermann et al. (2016)       | −75% in 2050 compared to 1990     | 8.7                 | 47             | ESM ↔ TIMES-PanEU                                    |
| Lotze-Campen et al. (2014)    | Not specified                     | 111                 | 18~62          | Various agricultural sector models                  |

Regional coverage is Europe.
Since current EU legislation does not allow for turning pasture into crops, land use effects of PBC cultures are expected to be higher on cropland, than with the inclusion of pasture land. Under the application of certain safeguards (e.g., directed at maintaining soil carbon and biodiversity), a change in EU legislation to allow for some lignocellulosic biomass production on pasture land may be adequate to mitigate crop price effects. In any case, land use strategies for PBC cultivation and their GHG mitigation effects need to be clarified and justified.

This study attempts to assess agricultural market impacts in the EU and the world due to PBC adoption in the EU within bioeconomy scenarios, which depict transitions from a fossil carbon-based society to a biomass-based society. These scenarios represent different biomass mixes with technological preferences toward the bioeconomy to achieve the GHG mitigation goal for the EU (−75% reduction in 2050 compared to 2005). We developed a model linkage that consists of an agricultural sector model (ESIM) to calculate biomass prices and an energy system model (TIMES-PanEU) to calculate biomass demand with given prices from ESIM. New PBC supply functions are developed in ESIM which simulates the explicit growth of PBC and how it substitutes other agricultural products on agricultural land. Equilibrium biomass supply and prices are estimated for bioeconomy scenarios within this model framework. A sensitivity analysis is conducted regarding factors such as crop and PBC yields as well as land uses for PBC. Simulation results can be useful to understand potential trade-offs of the bioeconomy in energy and agricultural systems.

2 | MATERIALS AND METHODS

2.1 | Agricultural sector model ESIM and PBC supply modeling

ESIM is a multicountry, comparative static partial equilibrium agricultural simulation model for the EU, West Balkan countries, Turkey, the United States, and the rest of the world (ROW) (Grethe et al., 2012). It can simulate changes in supply, demand, and prices for crops and livestock products with consideration of future macroeconomic trends, for example, for population and GDP, as well as alteration of agricultural policy. Furthermore, the first pillar of the Common Agricultural Policy (CAP) is modeled so that direct payments to farmers result in increasing producer incentives. Behavioral functions in ESIM are isoelastic. Processing industries are represented for dairy products, oilseeds, and 1G biofuels, for example, biodiesel and bioethanol. While supply in the EU consists of area allocation and yield functions, supply in the United States and the ROW, in contrast, is depicted only by supply functions, depending on world market prices without consideration of national policies. International trade among countries is modeled as net trade. Border policy instruments, for example tariff rate quotas, specific and ad valorem tariffs, intervention and threshold prices, and export subsidies, are represented in price transmission equations between international prices and domestic prices. All lignocellulosic biomass for the bioeconomy is aggregated as PBC and it is treated as a nontradable good in ESIM.

Previously, ESIM depicted area demand ($A_{c, crops}$ with $c$ being an index for countries and crops being an index for all crops including PBC, with crops1 as an alias) only as functions of own- and cross-producer prices ($P_{I}$) and land prices ($PL$). For this study, we added new features in the crop area demand function for PBC growth (Equations (1) and (2)) and its substitution to traditional crops (Equation (3)) in land supply markets with a finite land endowment (Equations (4) and (5)). The combination of Equations (1)–(5) determines the adoption of PBC and substitution of food crops. PBC can be cultivated on cropland, pasture, and marginal land in ESIM. Its effects on land use change depend on scenarios of PBC land use, PBC substitution parameters ($dis$ in Equation 3), market prices of agricultural products, and the diffusion of PBC in the nonagricultural market.

Area allocation functions are extended by a technical diffusion variable $D$ (Equation (1)). This variable reflects PBC development in agriculture and is defined by logistic functions (Equation (2)) to represent the nonlinear growth of PBC, following the adoption and diffusion of technology over the time horizon ($t$) ($elaspl$, $elaspl$ : elasticities of area demand with respect to crop prices and land prices, respectively).

\[
A_{c, crops,t} = \int_{c, crops} p_{I, crops, crops1}^{elaspl} PL_{c, crops, crops1}^{elaspl} D_{c, crops, t} \tag{1}
\]

The technical diffusion variable ($D_{c, pbc, t}$) represents the growth of PBC area to maximum PBC area levels by shifting area demand functions to the right, following the logistic growth curves with potential expansion ratios ($pt$). In this study, $pt$ is assigned with values so that PBC expand by ca. 10% of the agricultural area for each member state in the EU. The diffusion rate ($T$), which is an exogenous variable, increases annually over the time horizon. In addition, $D$ is affected by price change differences between the PBC price index ($index_{LB}$) and the crop price index ($index_{crops}$) with elasticities ($diff_{exp}$, $diff_{ka}$). Here, parameter $t_0$ indicates a midpoint value for a logistic curve while $\alpha$ is a scaling parameter.

\[
D_{c, pbc, t} = \begin{cases} 1 & \text{for } T = 1 \\ \frac{p_{I, index_{LB}, crops}^{diff_{exp}}}{1 + e^{-\frac{(T - t_0)^{diff_{ka}}}{\alpha}}} & \text{for } T > 1 \end{cases} \tag{2}
\]
Meanwhile, conventional crops (index crop, Equation (3)) are substituted with PBC in land markets with a fixed land endowment for agriculture. $D_{c,crop,t}$ is determined in Equation (3) and shifts food crop area supply functions to the left. $A_{lin}$ is an exogenous variable representing PBC area demand generated by TIMES-PanEU while ini_area is an initial agricultural area. The conventional crop area declines as PBC increase from the initial agricultural area. $dis_{c,crop}$ is a parameter which determines distributions of substituted crop areas due to PBC adoption. This parameter is based on estimated values (explained in the following section “PBC substitution on agricultural land”) of crop/pasture shares on land with high potential PBC yield. Land price ($PL$) change compared to the base level ($l_o$) also affects the level of substitution. Higher land price levels compared to the initial land prices contribute to larger cropland and pasture substitution with PBC.

$$D_{c,crop,t} = 1 - \frac{A_{lin}}{ini\_area_c} \cdot dis_{c,crop} \left(1 - e^{-k\left(\frac{PL_c - \xi}{\zeta}\right)}\right)$$  \hspace{1cm} (3)

Perennial biomass crops compete with traditional food crops in land markets modeled in ESIM. This follows the concept that a change in land supply or demand generates feedbacks via land rental prices as there is a finite agricultural land endowment (see Figure 2) (van Meijl, Rheenen, Tabeau, & Eickhout, 2006). An increase in the total agricultural area including conventional crops and PBC ($A_{tot}$) would affect land rental prices ($PL$). $PL$ is determined in Equation (5), and $A_{\_l}$ is a land limit asymptote (maximum agricultural land level) (See Table 2). Parameter $b$ and $sh$ indicate the slope and the horizontal position of land supply curves, respectively. Because land use change beyond the land limit asymptote is not considered, this can cause unrealistically high price levels in the nonlinear nature of Equation (5). For this study, we therefore constrain increases of land rental prices to the maximum level of 300%.

$$A_{tot,c,t} = \sum_{crops} A_{c,crop,t}$$  \hspace{1cm} (4)

$$A_{tot,c,t} = A_{l,c,t} - \frac{b_{c,t}}{sh_c + PL_{c,t}}$$  \hspace{1cm} (5)

### 2.2 PBC substitution on agricultural land

The cultivation area of PBC in Europe is currently rather insignificant. There are no regularly updated production statistics, but Lewandowski (2016) estimates an area of not more than 60,000 ha of PBC across Europe. In Germany, the agricultural area used for the cultivation of PBC area estimated to be about 11,000 ha (FNR, 2018). Although this area represents less than 0.1% of the total agricultural area, it grew strongly over the last decade. According to Schütte (2011) and FNR (2014), the production area in 2014 was 4.5 times the area in the year 2008. Although the growth rate has been stagnating lately, it is important to analyze how an increase in PBC production will affect other agricultural crops and pasture, considering the large future biomass demand (see Table 1).

Although this study has an EU focus, a scoping study has been conducted for the case of Germany to analyze which conventional crops are likely to be displaced by PBC. The basic idea of the chosen approach was to look at the composition of current crops and pasture on the agriculture area especially suited for PBC. We used data from the German Agricultural Survey 2010 (FSO/SOL, 2011) on the current area grown to grassland and crops such as summer wheat, winter wheat, rye, triticale, barley, oats, maize, sugar beets, potatoes, and winter rape at the NUTS 3 (district) level (see Supporting information Figure S1). GIS data on the growing potential of PBC on land currently used for agricultural production were derived from studies on the growth potential of miscanthus (Schorling, Enders, & Voigt, 2015) and SRC (Aust et al., 2014) in Germany (see Supporting information Figure S1, Table S1 and S2 for the agronomic properties of the different growth classes).

From current production statistics, we calculated the absolute area of each crop grown on high or very high potential land for PBC (Figure 3a, left-hand axis) and the shares of PBC potential in each area item (Figure 3a, right-hand axis). These areas/shares represent the potential reduction of the production area of each crop/pasture due to PBC cultivation. The area estimation is based on NUTS 3 level data and was
| Country   | Cropland | Pasture | Total | Maximum agricultural landa |
|-----------|----------|---------|-------|----------------------------|
| Germany   | 12.1     | 4.6     | 16.6  | 18.3                       |
| France    | 18.1     | 9.6     | 27.7  | 30.4                       |
| Italy     | 7.1      | 4.0     | 11.1  | 12.2                       |
| Spain     | 9.5      | 8.5     | 18.0  | 19.8                       |
| UK        | 6.0      | 10.1    | 16.1  | 17.7                       |
| Poland    | 12.3     | 3.4     | 16.0  | 19.0                       |
| Romania   | 7.8      | 4.7     | 12.5  | 14.9                       |
| Total (ESIM) | 102.3   | 61.8    | 164.1 | 186.1                      |
| Total (Eurostat) | 104.3  | 59.6    | 164.0b | 213.6c                     |

*aFor ESIM, maximum agricultural land for agriculture is calculated by using the base year agricultural area and assuming a land surplus for the EU15 of 10% and for the EU13, of 20% of the existing agricultural area. bUtilized agricultural area, including permanent crops, in EU28, is 175 Mha in 2013. cTotal farm area data in Eurostat are shown.

**TABLE 2** land use statistics for EU countries. ESIM database is from the year 2008. For Eurostat, farm area is shown in the table as maximum agricultural land.

**FIGURE 3** Part (a): Absolute area (Mha, bars) of crops/pasture grown on high or very high PBC potential land and shares (%. diamonds) of high or very high PBC potential in each crop/pasture or area item in Germany. Part (b): Area shares of crops/pasture on land with high or very high agronomic potential of PBC in total PBC potential area, and area shares of crops/pasture in total agricultural area in the ESIM database.
aggregated to the national level. This is in accordance with ESIM, where agricultural supply is modeled at the national level. In the analysis, only agricultural land with high and very high growth potential for PBC was considered. According to our calculations, this encompasses an agricultural area of ca. 6.7 Mha (ca. 40% of the total agricultural area in Germany), of which ca. 3.2 Mha is grassland and ca. 3.5 Mha is cropland.

By using the data presented in Figure 3a, we calculated which crops are likely to be most replaced at the national level in the EU by the establishment of PBC (see Figure 3b). Each gray bar represents area shares of crops/pasture in total land with high/very high agronomic PBC potential. Those shares are relatively similar to area shares (black bar) of crops/pasture in total agricultural area in the ESIM database, with slight differences for some crops and a strong difference for pasture: Pasture, and to a lesser extent silage maize, has substantially higher shares in high/very high PBC potential land, than in land in the ESIM database. We therefore derive the conclusion that increasing PBC production will substitute silage maize and pasture over-proportionally. As a result, and when only agronomic potential and related higher profits are considered in farm management decision making, about 45% of PBC area would be on former pasture while 15% and 11% of PBC area would be land formerly grown to wheat and silage maize, respectively. When phasing in PBC according to the diffusion variable \( D \) (see above), we use these shares for an equivalent shift of area allocation functions of pasture and other crops to the left. For other EU member countries, pasture shares in the PBC area are assumed to be at the same level as in Germany\(^2\), but crop area being replaced by PBC is set according to existing crop area shares in each country. It must be noted, however, that the PBC area considered in our analysis only represents a set of technical and agronomic factors of PBC potential and does not take into account legal regulations (e.g., prohibitions to establish PBC in protected areas), terrain, or socioeconomic restrictions. Although these aspects are seriously reducing the attractiveness for farmers to grow PBC (Lewandowski, 2016), it is justified to not take them into consideration here due to the long-term focus of our study.

### 2.3 | PBC yield assumptions until 2050

PBC yields vary depending on climate conditions, soil types, and water availability in the EU. For this study, we adapted aggregated PBC values based on two land types: good agricultural land and marginal land. Average PBC yields were derived for short-rotation coppice, such as willow and poplar, as well as for miscanthus, a perennial grass, based on the assumption of equal shares. Miscanthus, especially, is a very promising lignocellulosic biomass crop due to its high yield potential (Iqbal et al., 2015) and manifold utilization possibilities (Lewandowski, 2016). We considered that lignocellulosic biomass crops have higher yields (12.5 ton ha\(^{-1}\) year\(^{-1}\)) on cropland and lower yields (8.7 ton ha\(^{-1}\) year\(^{-1}\)) on pasture and marginal land in ESIM (see Table 3 for references). In field trials, it was demonstrated that, for example, miscanthus yields on good agricultural land can be significantly higher than the assumptions applied in the current study (Iqbal et al., 2015). In conclusion, yield assumptions, both for miscanthus and SRC, are rather conservative, due to potential semicommercial scale cultivation and biomass losses during

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**Table 3: Assumptions about current PBC yields for this study**

| Crop       | Land type      | Yield ton ha\(^{-1}\) year\(^{-1}\) (dry matter) | Comment                                      | References                                      |
|------------|----------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------------|
| Miscanthus | Good agricultural land | 13.6                                         | Based on four sites in Europe                 | Lewandowski et al. (2016) and Wagner, Kiesel, Hastings, Iqbal, and Lewandowski (2017) |
| Miscanthus | Marginal land   | 9.7                                           | Based on two sites in Europe                  | Lewandowski et al. (2016) and Wagner et al. (2017) |
| SRC        | Good agricultural land | 11.4                                         | Based on the land class which is “favorable” for SRC | Aust et al. (2014) |
| SRC        | Marginal land   | 7.6                                           | In case of 1) based on land class which is only “medium” suitable for SRC (7.5) In case of 2) 7.6 | 1) Aust et al. (2014) 2) Schweier, Schnitzler, and Becker (2016) |
| Average    | Good agricultural land | 12.5                                         | Cropland in ESIM                              |                                                 |
| Marginal land |                                          | 8.7                                           | Pasture and marginal land in ESIM              |                                                 |

\(^2\)For Denmark and Sweden, only 10% of PBC area is given as a share of pasture because absolute pasture areas are small in those countries.
harvesting and drying (Searle & Malins, 2014). PBC yields are assumed to enhance by 30% in the EU until 2050 to take into account technical progress in PBC (own assumption comparable to cereals, see Table 5).

2.4 | Energy system model TIMES-PanEU

The Pan-European TIMES Energy System Model (TIMES-PanEU) is an energy system model comprising all EU28 countries as well as Switzerland, Norway, and Baden-Württemberg (Blesl, Kober, Bruchof, & Kuder, 2010). The modeling period extends from 2010 to 2050 with 5-year time steps. The objective function of the model is the minimization of the total discounted energy system costs for the time horizon 2010 to 2050. Furthermore, the framework conditions regarding energy taxes and subsidies are included in the calculation. As an energy system model, TIMES-PanEU represents all sectors, concerning energy supply and demand, such as the raw materials supply sector, public and industrial electricity and heat generation, industry, trade, services, households, and transport. This model enables us to determine the economically optimal energy supply structure with a specified energy service requirement and, if necessary, energy and environmental policy specifications. A greenhouse gas reduction target at European level is implemented through the EU Emissions Trading System (ETS). The ETS covers emissions from power generation, energy-intensive industries, and aviation. Compared to 2005, the corresponding emissions will be reduced by 75% by 2050 in all scenarios considered. In addition, a cross-sector greenhouse gas reduction target was implemented at the national level in Germany and at the state level in Baden-Württemberg for specific scenarios.

For this study, a special focus was placed on bioenergy sources and their paths of use. The model distinguishes eight biomass supply categories: organic waste, oilseeds, starch crops, sugar crops, waste wood, land scrapping residues, wood from forestry, and woody crop from agriculture (See Table 4). Biomass is transformed into various energy end uses and energy carriers: biogas, biofuels, heat, and electricity. The Bioenergy Carbon Capture and Storage (BECCS) technology is not accounted for as a GHG mitigation option in this study. Since biomass is generally regarded as not economically transportable over long distances due to its relatively low energy density, it is produced and used locally, that is, at the national level. Biofuels, however, have a higher energy density and can therefore be traded internationally in TIMES-PanEU.

In addition, we take the chemical/material use of biomass into account as exogenous demand from the chemical industry as well as the building materials and furniture industries. An increase of the exogenous demand of material biomass use represents technological progress, political conditions, or consumer preferences. For consideration of biomass competition between energy and chemical/material uses, the exogenous demand of chemical and material use biomass competes for the same biomass potentials as the energy sector. This induces endogenous changes in biomass demand and biomass end use in the energy sector driven by changes in material demand.

2.5 | Model linkage between ESIM and TIMES-PanEU

Bioeconomy scenarios are simulated in a soft linkage model system between TIMES-PanEU and ESIM (Figure 4)
while biomass groups in each biomass use are harmonized between two models as in Table 4. The linked model system finds internally consistent market equilibriums in the energy system and agricultural markets for GHG mitigation. The linkage is implemented differently in 1G biomass and 2G biomass sectors. Regarding 1G biofuels, ESIM includes 1G biofuel processing industry and represents more diverse crops than TIMES‐PanEU. ESIM receives 1G biofuel demand and domestic biofuel production from TIMES‐PanEU and calculates aggregated price indexes such as starch crops and oilseeds. Those price indexes are given back to TIMES‐PanEU. For biogas and 2G biomass-based energy, relative biomass price changes simulated in ESIM directly affect biomass feedstock prices in the energy system in TIMES‐PanEU because ESIM does not have processing industry for those biomass processes. However, biomass price feedbacks are not accounted for in the chemical/material sector because it is not modeled in TIMES‐PanEU. Biomass trade is restricted in TIMES‐PanEU so that 1G biomass trade effects are simulated in ESIM. However, 1G and 2G biofuels are traded in TIMES‐PanEU. Regarding trade of 1G biofuels, trade is initially calculated in TIMES‐PanEU based on price differences of biofuels between the EU and the world. In the model linkage via exchange of demand and domestic production, ESIM receives trade data from TIMES‐PanEU for trade between EU and rest of the world and provides relative changes in biomass and global biofuel prices as feedbacks to TIMES‐PanEU.

For this project, TIMES‐PanEU and ESIM share the initial biomass price trends until 2050 which reduces iteration numbers for seeking an equilibrium. Because price elasticities of biomass demand in TIMES‐PanEU are lower than price elasticities of biomass supply in ESIM4, average

4The price elasticity of demand should be higher than the price elasticity of supply in order to reach iteration converge.
biomass prices based on previous prices and new prices from TIMES-PanEU are calculated and these prices (expected biomass market prices) are mapped to ESIM. To find an equilibrium, iterations are conducted until biomass price and demand variables converge to <5% differences. On average, the equilibrium is reached within five iterations.

2.6 Bioeconomy scenarios

Bioeconomy scenarios depict different societal transitions to a bioeconomy. Table 5 shows macroeconomic trends and assumptions on agricultural market development until 2050, which are shared in all bioeconomy scenarios. Regarding macroeconomic trends, the growth of population and GDP in the EU follows the EU reference scenario from EC (2013) both in ESIM and TIMES-PanEU. For the global food market simulation, ESIM follows the projection of EIA (2013) in population and GDP growth. For the EU, crop yield improvement is derived from own assumptions based on historical trends. For the ROW, crop yields increase until 2050 to be consistent with the global food market projection from FAO (Alexandratos & Bruinsma, 2012). World food prices of cereals, oilseeds, and meat come from the projections of Fischer et al. (2009). We calculated these price projections by adding average price differences from various additional biofuel demand scenarios to the basic price projection, which represents no further expansion of 1G biofuels after 2008 (scenario REF-01). Regarding the EU agricultural policy, the EU gradually reduces the first pillar of direct payment to farmers in the CAP and tariff barriers, for example, tariff rate quota, and ad valorem and specific tariff, in agricultural trade. Agricultural markets in the EU are liberalized by 2030.

We simulate five scenarios which were defined by a larger working group of modelers from the Bioeconomy Research Program Baden-Wuerttemberg.5 These scenarios comprise different potential futures of the bioeconomy. They share certain features, and they differ from each other regarding other features. Next to a no bioeconomy scenario (No_bio), scenarios include a business as usual scenario (Bio_bau), a scenario with a somewhat stronger development of the material use of biomass (Bio_mid) and two scenarios with a very strong development of demand for the material use of biomass, one with unchanged dietary preferences (Bio_hi) and one with a more sustainable food consumption (Bio_hi + diet). All scenarios are defined at the EU level, as well as at the national level (Germany) and the regional level (Baden-Württemberg). No changes are assumed in biomass supply and demand functions in the world out of the EU, but agricultural supply and demand outside of the EU react to any changes in international prices which are caused by the implementation of the EU scenarios. Table 6 gives an overview of the four scenarios.

Bioeconomy narratives and their technical implementation are explained in more detail in Tables 6 and 7, respectively. The bioeconomy scenarios aim to substitute fossil energy with renewable biomass resources while reducing GHG emissions (~75%), and meeting goals in renewable electricity generation (80%) and renewable energy in gross end-use energy (60%). As a reference scenario, “No_bio” represents that no further energy policy affects the agricultural sector until 2050. No coupling is implemented in ESIM with TIMES-PanEU, while only 1G biofuel supply and demand changes with respect to fossil oil and biofuel input prices. The “Bio_bau” scenario represents expansion of the bioeconomy based on the current traditional bioenergy system and food biomass. Especially, it includes no restriction on 1G biofuels in transport. The “Bio_mid.”

5https://biooekonomie-bw.uni-hohenheim.de/en
“Bio_hi,” and “Bio_hi + diet” scenarios represent levels of transformation in biomass end-use in the energy, material, and food systems following political aims of the bioeconomy (See Table 7). “Bio_hi” differs mainly from “Bio_mid” in that biogas is not used anymore and biomass use for new chemical/material applications increases

### TABLE 6 Description of bioeconomy scenarios

| Scenario     | No_bio | Bio_bau | Bio_mid | Bio_hi | Bio_hi + diet |
|--------------|--------|---------|---------|--------|---------------|
| Political aims | No further energy policies with effects on the agricultural sector | Climate and energy policy targets are achieved on all geographical scales |
| Energy and material use | Only supply and demand of 1G biofuels changes responding to fossil oil and agricultural price trends | ● No change in current (traditional and innovative) material use | ● Slightly improved relevance of the traditional use of biogenic materials | ● Expansion of the traditional use of biogenic materials |
| Nutrition | No change in current dietary habits | Lowering food waste and demand for animal food products |

### TABLE 7 Technical specification of bioeconomy scenarios at the EU level

|                     | Bio_bau | Bio_mid | Bio_hi | Bio_hi + diet |
|---------------------|---------|---------|--------|---------------|
| GHG mitigation in ETS | –75% compared to 2005 | | | |
| Renewable electricity generation | 80% in 2050 | | | |
| Renewable energy in gross end-use energy | 60% in 2050 | | | |
| Biomass trade | No biomass trade in food crops, PBC and forestry in TIMES-PanEU, 1G biomass trade allowed in ESIM | | | |
| Biofuels in transport | | | | |
| Min⁴ | 10% share until 2020 then constant | 10% share until 2020, 0% of 1G biofuels afterward in transportation | | |
| Max | No restriction | 0% of 1G biofuels after 2030 in transportation | | |
| Biogas electricity generation | | | | |
| Min | Current level⁵ | Current level until 2030, banned afterward except for biogas from waste | | |
| Max | Trend | Trend until 2030, banned afterward except for biogas from waste | | |
| Biomass in chemical, material use | | | | |
| Traditional use | No change | Annual growth at 1.7% | Annual growth at 2.0% | |
| Innovative chemical, material use | No change | Annual growth at 5.5% | Annual growth at 8.1% | |
| Diet change⁶ | No restriction | | Cereals, rice, sugar, potato, eggs, plant oils (–10%), Meat products (–41.1%), Milk and dairy products (–29.7%) |

⁴Minimum biofuel use represents the EU biofuel quota. ⁵For Germany, biogas plants decline following a decommissioning curve due to energy policy changes (EEG). ⁶Diet change takes effect from the year 2015 on and stepwise results in the aggregate reduction rates by 2050.
further. The amount of chemical/material use of biomass is estimated from Piotrowski, Essel, Carus, Dammer, and Engel (2015) (see Supporting information Table S4).

### 2.7 Sensitivity analysis

In addition to bioeconomy scenarios, we conduct a sensitivity analysis with a focus on the effects on the food price index, the land rent price index, and agricultural area, considering three factors: land use of PBC, crop yields, and PBC yields. These sensitivity analyses are simulated in ESIM only without iteration with TIMES-PanEU. In the sensitivity analysis, we simulate each bioeconomy scenario for different options of PBC land use: “only cropland” and “marginal land.” While the standard formulation is that PBC can be grown on cropland as well as on pasture, “only cropland” assumes that PBC mainly substitute on cropland, constituting higher PBC yields than on pasture and marginal land. The parameter \( \text{dis} \) (see Equation (3)) about PBC substitution on agricultural land is changed so that pasture is not replaced and PBC only replace crop area according to each crop’s area share in the total crop area. For the sensitivity analysis “marginal land,” PBC area increases without replacing agricultural land and the parameter \( \text{dis} \) becomes zero. PBC are cultivated mainly on marginal land. Here, it is assumed that an additional 30% of land which has low productivity and is currently not used for farming is allowed for PBC cultivation. Technically, this scenario is implemented by shifting the asymptote of the agricultural land supply function. In this simulation setting, PBC penetration in the agricultural market does not directly replace conventional crops, but changes in the land rent price could affect conventional farming to some extent. Finally,

![Table 8](https://example.com/table8.png)

**TABLE 8** Biomass demand (EJ) and biomass area (Mha) for the bioeconomy in 2050 in the bioeconomy scenarios

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*aForestry biomass is not simulated in ESIM, and numbers are from TIMES-PanEU. bChemical/material biomass use is exogenously given to TIMES-PanEU for bioeconomy scenarios. cFor this calculation, total agricultural area (175 Mha) for the EU is used (see Table 2).
regarding conventional crops and PBC yield development, ±10% yield levels of crops (excluding pasture) and PBC by 2050 are compared to the central estimate for all scenarios.

3 | RESULTS

3.1 | Biomass demand and land use change

Table 8 shows biomass demand and the agricultural area used for the bioeconomy in our scenarios. Biomass demand from agriculture significantly increases where total biomass demand amounts to 9.7–10.5 EJ. PBC account for about 50.6%–76.3% of biomass demand with its share increasing toward the extensive bioeconomy (Bio_hi, Bio_hi+diet). We find that total area for energy and chemical/material biomass is 42.4–46.3 Mha (24.2%–26.5% of agricultural area in the EU). With scenarios changing toward the extensive bioeconomy, increasing material use of biomass contributes to higher total biomass demand. Land demand, however, slightly decreases in “Bio_hi” and “Bio_hi + diet,” especially compared to “Bio_mid” because PBC substitute 1G biomass and PBC have a higher land use efficiency than 1G biomass. Additionally, “Bio_hi + diet” shows the higher biomass demand from agriculture than “Bio_hi.” This shows that diet change has effects on reducing biomass prices and can result in increasing biomass supply for the bioeconomy.

The bioenergy share in final energy consumption significantly increases from 8% in 2010 to 20%–25% in 2050 for GHG mitigation and renewable energy targets (Table 8). Looking at the final use of biomass, Figure 5 shows that the focus of the energetic use of biomass is on PBC and forestry biomass for industrial heat production as well as electricity/heat production in power plants and residential heat. In the scenario “Bio_bau,” biomass is mainly used for biogas, biodiesel, and heat production in industry. In “Bio_hi,” material use of biomass increases at the expense of biomass use for Fischer–Tropsch diesel production due to higher biomass competition than under “Bio_bau” and “Bio_mid” and at the expense of biogas and bioethanol. In addition, some biodiesel is still used to decarbonize machinery in agriculture as well as residential, commercial, and industrial sectors. But 1G bioethanol use substantially declines in bioeconomy scenarios due to increased feedstock prices from cereals except for the scenario “Bio_bau”.

Land use change is shown in Table 9. Even though we allow for penetration of PBC on agricultural area, the amount of agricultural land increases by 7.4 to 8.1 Mha in all bioeconomy scenarios because higher food prices due to market feedbacks increase agricultural land demand. New agricultural land not under cultivation before is sourced from marginal surplus land for PBC as shown in Figure 2. “Bio_hi” shows the largest increase in new agricultural land because of high PBC penetration on conventional agricultural area and increasing land demand for food production. Diet change in the scenario of “Bio_hi + diet” decreases the cultivation of new agricultural land compared to “Bio_hi.” This is
because lower meat consumption requires less animal feed and thus agricultural land. However, these effects are rather small compared to the level of reduction in meat and dairy consumption.

### 3.2 Agricultural market impacts

For food prices, bioeconomy scenarios show increases in the price index by about 11% in the EU compared to “No_bio” in 2050, with the exception of the scenario with low animal product diets (Bio_hi + diet), where the price increase is only about 3% (Table 10). High biomass demand for energy and chemical/material use imposes high impacts on agricultural markets in all bioeconomy scenarios without changes in meat diet. Cereal and oilseed prices increase by about 8%–16% and 20%–39%, respectively. Increases in oilseed prices are the highest among products because of high demand for oilseeds for decarbonization in transportation, industry, and machinery in agriculture (Table 8, Figure 5). “Bio_hi” scenario shows lower price impacts on the food price index than the “Bio_bau” and “Bio_mid” scenarios. This shows that substitution of food-based bioenergy, for example, biodiesel and biogas, by PBC-based bioenergy has effects on reducing increases in food prices. In the scenario “Bio_hi + diet,” the food price index increases substantially less due to lower meat and cereal prices compared to the other scenarios.

PBC prices increase by 71%–84% in 2050 compared to the year 2010. High PBC demand (Bio_hi) shows the highest increase in the PBC price. High increases in PBC prices are affected by two factors: high biomass demand and low PBC area diffusion rates. Autonomous PBC area diffusion rates are set to reach 10% of initial agricultural land until 2050. In addition, the increasing PBC/food price index ratio results in higher diffusion rates, but this effect is not large enough to offset price increases due to PBC demand.

Moreover, the land rent index increases by 60%–70%. The “Bio_mid” and “Bio_hi” scenarios show the largest increase in the land rent index because of the highest increases in agriculturally used land among all scenarios. Diet change in the “Bio_hi + diet” scenario results in reduced impacts on land rents, but still shows a high (60%) increase in land rent. This can be contributed to the development of agricultural area in Table 8: Even with diet change, cultivated agricultural area remains similar to other scenarios because meat and dairy products are exported by the EU to a stronger degree, than under other scenarios.

Regarding price changes in the ROW, average product prices increase by about 5% under all bioeconomy

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**Table 9** Land use change (Mha) in the EU in 2050. Numbers in parentheses indicate differences between scenarios and a reference without the bioeconomy (No_bio).

|                | No_bio | Bio_bau   | Bio_mid   | Bio_hi    | Bio_hi + diet |
|----------------|--------|-----------|-----------|-----------|---------------|
| Cropland without PBC | 104.8  | 97.8 (−7.0) | 94.4 (−10.4) | 90.5 (−14.3) | 89.9 (−14.9) |
| Pasture without PBC  | 61.4   | 55.1 (−6.3) | 52.6 (−8.8)  | 50.0 (−11.4) | 50.1 (−11.3)  |
| PBC               | 20.7   | 27.2       | 33.8       | 33.8       |               |
| Total (cropland+pasture+PBC) | 166.2  | 173.6 (+7.4) | 174.2 (+8.0) | 174.3 (+8.1) | 173.8 (+7.6) |

**Table 10** Changes in price indexes in the EU with bioeconomy scenarios by 2050 (index year 2010 = 100).

|                | No_bio | Bio_bau (Diff) | Bio_mid (Diff) | Bio_hi (Diff) | Bio_hi+diet (Diff) |
|----------------|--------|----------------|----------------|---------------|--------------------|
| Food Cereals   | 123.1  | 138.4 (+15.3)  | 136.9 (+13.8)  | 138.7 (+15.6) | 131.0 (+7.9)       |
| Oilseeds      | 111.7  | 142.7 (+31.0)  | 151.0 (+39.3)  | 152.7 (+23.5) | 151.8 (+20.1)      |
| Raw milk      | 105.7  | 107.8 (+2.1)   | 107.9 (+2.2)   | 107.9 (+2.2)  | 104.0 (−1.7)       |
| Meat          | 114.8  | 117.6 (+2.8)   | 117.8 (+3.0)   | 118.1 (+3.3)  | 107.3 (−7.5)       |
| Total index   | 105.4  | 116.5 (+11.1)  | 116.4 (+11.0)  | 116.2 (+10.8) | 108.4 (+3.0)       |

PBC Index |  100.0  | 171.6 (+71.6)  | 183.9 (+83.9)  | 182.6 (+82.6) | 175.8 (+75.8)      |
| Land rent    |  127.2  | 187.0 (+59.8)  | 196.7 (+69.5)  | 196.3 (+69.1) | 187.0 (+59.8)      |

Notes: Differences (Diff) are calculated compared to the no bioeconomy (No_bio) baseline. The total price index is calculated, considering agricultural product prices in this table.
scenarios, except for “Bio_hi + diet” (Table 11). Cereal prices increase up to 8.6% due to fewer cereal exports from the EU. Oilseed prices are also affected substantially (+9.0%–15.6%) by an increase in EU oilseed demand for biodiesel in transportation. The meat diet scenario (Bio_hi+diet) shows that increases in average food prices can be substantially reduced in the ROW, resulting from lower EU consumption and higher EU exports of meat and dairy products.

3.3 | Sensitivity analysis with respect to PBC land use options and biomass yields

We conduct sensitivity analyses and analyze the effects on three indicators: the food price index, the land rent index, and the increase in agriculturally cultivated land. Simulations are based on ESIM as a stand-alone version with different simulation set-ups regarding land use for PBC and yield growth rates for traditional crops and PBC.

The food price index shows high variability with respect to crop yields: A 10% difference in crop yields leads to changes from −20% to +30% in EU and global food price indices, reflecting relatively price inelastic demand for food. In contrast, changes in PBC yields impose only small impacts on all indicators. This is due to the fact that PBC demand is considered constant and the area which is not used anymore by PBC production due to the yield increase is distributed among somewhat more other crops, somewhat less marginal land use and more grass production on pastures. Pasture prices, though, are not included in the reported price index, which therefore changes only slightly. Furthermore, variants of considered factors in sensitivity analysis have limited effects on the land rent price index because bioeconomy scenarios in the “Base” setting already put strong pressure on the land rent price index and additional land demand.

The “only cropland” use of PBC shows higher increases in the food price index because PBC directly reduce food production in the EU (Figure 6), but it can contribute to lower increases in land rent prices, as in total the demand for existing agricultural land increases less and substitution of pasture does not take place (Figures 7 and 8). On the other hand, employing marginal land for PBC (“only marginal”) shows lower impacts on food prices than other land use options, but still results in market impacts to some extent (Figure 6). This is because higher land prices due to land use competition cause less food production. The PBC land use on marginal land shows about 5% increases in market prices. With diet change (Bio_high+diet), changes in the food price index become negative compared to the “No_bio” scenario. However, PBC cultivation on marginal land requires about 30–42 Mha land in addition to existing agricultural land (Figure 8).

4 | DISCUSSION

The bioeconomy scenarios analyzed in this paper represent biomass demand changes caused by biomass use for energy and chemical/material production. The coupled modeling system (ESIM & TIMES-PanEU) analyzes multidimensional effects at the nexus across climate, energy, food, and land. We focused on how bioeconomy development would potentially affect food prices and land use change by 2050.

4.1 | Biomass demand for the bioeconomy until 2050

Biomass use for the bioeconomy will be determined by technological progress of biomass processing technologies, biomass feedstock prices, and prices for fossil-based substitutes. The future development of these drivers is uncertain. Based on central assumptions, our simulation results show high PBC prices (increases about 72%–84% compared to a “business as usual (No_Bio)” in 2050) and high PBC demand (4.9–8.0 EJ) for the bioeconomy. This is because final products derived from PBC, for example, heat, fuels, and electricity, are considered cost-effective technical options in the energy system not only to meet GHG mitigation targets, but also political goals related to the generation of renewable electricity and shares of renewable energy in gross end-use energy. These multiple boundary conditions make the demand of biomass

### Table 11

|          | No_bio | Bio_bau | Bio_mid | Bio_hi  | Bio_hi+diet |
|----------|--------|---------|---------|---------|-------------|
| Cereals  | 135.3  | 143.4 (+8.1) | 142.7 (+7.4) | 143.4 (+8.1) | 138.8 (+3.5) |
| Oilseeds | 122.8  | 135.9 (+13.1) | 138.4 (+14.6) | 131.8 (+9.0) | 128.3 (+5.5) |
| Raw milk | 133.9  | 133.9 (+0.0) | 133.9 (+0.0) | 133.9 (+0.0) | 132.8 (−1.1) |
| Meat     | 139.1  | 141.6 (+2.5) | 141.8 (+2.7) | 142.1 (+3.0) | 132.7 (−6.4) |
| Total    | 133.9  | 139.0 (+5.1) | 138.9 (+5.0) | 138.9 (+5.0) | 131.9 (−2.0) |

**Notes:** Differences (Diff) are calculated compared to the no bioeconomy (No_bio.) baseline. The total price index is calculated, considering agricultural product prices in this table.
**FIGURE 6**  Sensitivity analysis regarding the EU (upper) and world (lower) food price index related to land use options for PBC, crop and PBC yields. Changes in the price index are relative to the “No_bio” scenario in 2050. For land use, “High” and “Low” indicate “only cropland” and “marginal” land use for PBC. For crop and PBC yields, “high” and “low” indicate 10% higher and 10% lower yields in 2050 compared to the base parameters assumed in this study.

**FIGURE 7**  Sensitivity analysis regarding the EU Land rent price index related to land use for PBC, crop and PBC yields. Changes in the price index are relative to the “No_bio” scenario in 2050. For land use, “High” and “Low” indicate cropland and marginal land use for PBC. For crop and PBC yields, “High” and “Low” indicate 10% higher and 10% lower yields in 2050 compared to the base parameters assumed in this study.
in TIMES-PanEU less price-elastic. In addition, increasing use of PBC in the production of materials/chemicals contributes to high future PBC demand. PBC prices are determined mainly by PBC demand and land being cultivated with PBC. Both drivers are represented in ESIM. Here, the assumption about PBC diffusion rates plays a major role in PBC prices. Lauri et al. (2017) show that global forestry biomass prices could double in the late 21 century due to high biomass use competition to meet the 2°C climate target and thus find effects of a similar order of size. We emphasize that such results are based on the current perspective on future technical change. Therefore, the outlooks on technology change being part of the ESIM as well as the TIMES-PanEU formulation should be regularly updated because the emergence of new technologies could hamper as well as stimulate the bioeconomy substantially.

4.2 Bioeconomy impacts on agricultural markets in the EU and the ROW

We explicitly modeled area substitution of cropland and pasture with PBC. Our data analysis for Germany shows that high PBC production is likely to happen to a large extent on current crop area. Fischer et al. (2009) support that, in some other EU countries, PBC have very high potential (13–19 tons/ha, dry mass) on large shares (14%–53%) of agricultural land. A bottom-up assessment for other EU member states would help to pinpoint the specific crops that are most likely to be replaced by PBC, considering economic conditions and yield potentials in other EU countries as well.

Our results show that biomass demand for the bioenergy has a strong potential to affect EU and global food prices compared to a business as usual scenario (No_bio). Especially, high impacts were on cereals (7.9%–15.3%) and oilseeds (20.1%–39.3%) in the EU. The ROW is affected less, but still prices increase substantially for cereals (3.5%–8.1%) and oilseeds (5.5%–15.6%) due to increasing food imports to the EU. Our scenarios include EU market liberalization in agriculture, including the abolishment of direct payments and tariff barriers. In less liberalized markets, price impacts may be higher on domestic markets and lower on world markets.

Our results are in contrast with studies based on engineering and geographic disciplines which avert conflicts with food security by employing an approach based on the “food first principle” and freed-up surplus. A review study from Kluts, Wicke, Leemans, and Faaij (2017) reports that those studies project freed-up surplus land for energy crops in the EU by about 7%–48% of arable land and 23%–28% of pasture land by 2030. These studies are mainly based on simple land allocation models which are not able to capture complex market dynamics involving the political framework, international trade, and specific features of the agricultural sector such as the fixed production factor land. Furthermore, integrated assessment model-based studies (Daioglou, Wicke, Faaij, & Vuuren, 2015; van Vuuren, Bellevat, Kitous, & Isaac, 2010) often employ results from the studies based on freed-up surplus land (often called “abandoned land”) projections with the “food first principle” which also project large global bioenergy uses without any conflicts with food security. However, in reality, agricultural land use has been decreasing in the
EU for the last several decades due to urbanization, agricultural intensification, and farmland abandonment (EPA, 2017) and the current agricultural land declining rate is estimated at about 0.6 Mha per year for the period of 2007–2016. This rate is projected to decline until 2026 (OECD/FAO, 2017). In conclusion, PBC substitution on agricultural farmland is increasingly likely rather than the cultivation of PBC on freed-up land unless EU agricultural policy changes toward more intensive farming, which is unlikely seen the strong societal interests in environmental protection and animal welfare.

4.3 PBC land use implications on agricultural markets

Land use for PBC has strong implications for agricultural markets and environmental impacts. Marginal land use for PBC has been claimed as the new land potential for PBC because it is generally viewed that it would not compete with food crops (Chum et al., 2011). However, the current marginal land area is viewed as small (1.35 Mha) in the EU (Allen et al., 2014) and the arable land expansion potential decreases. As a scarce resource, an increase in land demand will affect farming of food crops by increasing input costs, especially land rents, as shown in Bryngelsson and Lindgren (2013). Strict rules could be applied that allow PBC cultivation only on marginal land, but policy-monitoring costs would be high.

Finally, using marginal land for PBC has several disadvantages such as high investment costs for crop establishment and potentially high biomass transportation costs. In addition, land use conversion from pasture and marginal land to PBC cultivation bears the risk of increasing carbon emissions from soil carbon stocks and potentially negative effects on biodiversity. Thus, some authors recommended PBC cultivation only on soils with low carbon stocks (Whitaker et al., 2018) or landscapes, where lack of structures reduced their habitat functions. A suitable land mix of arable land, pasture, and marginal land should be sought with strict sustainability conditions regarding soil carbon preservation.

4.4 Effects of diet change and biomass yields on the bioeconomy

According to our results, dietary change toward fewer animal products and improving crop yields are effective measures to address food price increases. This implies that nonfood biomass demand for the bioeconomy and GHG mitigation cannot be achieved in a sustainable manner without transforming current agricultural systems and dietary habits. However, in our scenario specification, we do not find much agricultural land abandonment in the EU due to dietary change because less meat demand does not directly affect livestock production but rather leads to an increase of meat exports from the EU to the ROW (Choi & Entenmann, 2019). GHG emissions from the livestock sector would remain at a similar level in this scenario. But as intensive animal production in the EU involves substantial environmental externalities (Leip et al., 2015) as well as deficiencies of animal welfare (Grethe, 2017), such dietary change may be accompanied by stricter environmental and animal welfare requirements resulting in lower EU production as well. Finally, a challenge will be to reach crop yield improvement in a way which does not reduce the environmental sustainability of current cropping systems in the EU.

4.5 Limitations of modeling bioeconomy scenarios

The complexity of the bioeconomy and the energy system is high. Results of this study should therefore be interpreted within the limitations of the ESIM and TIMES-PanEU models as well as the scenario definitions chosen. ESIM does not depict total agricultural area and excludes permanent crops, most vegetables, and some industrial crops (Table 2). If PBC are cultivated on larger agricultural land including permanent crops and vegetable area, market impacts may be less than shown in our results. However, our scoping analyses indicate that cereals, maize, and pasture have the highest chances to be substituted with PBC.

Moreover, this study focuses on the large-scale plantation of PBC in the EU by assuming technological options in each bioeconomy scenario. PBC supply follows, to a certain degree, autonomous diffusion processes of PBC land supply based on assumptions about diffusion levels. In reality, such growth dynamics and resulting prices would be affected by various factors such as governmental support for biomass cultivation and maturity of biomass markets (Alexander et al., 2013), factors not explicitly modeled in this study.

Regarding nonfood biomass other than PBC, crop residues are not considered as biomass feedstock in this study and forestry biomass potential including forestry residues is fixed as an exogenous parameter. PBC and forestry biomass are treated as nontradable goods in ESIM and TIMES-PanEU. Even though these assumptions on biomass potential of residues and forestry biomass are conservative, they appear to be realistic due to reasons explained in the introduction. However, if the PBC price relative to food prices becomes higher in 2050, as simulated under our scenarios, crop residue use may expand and the trade of woody biomass could be stimulated in the global market. The ROW can also produce PBC on marginal surplus land, which is considered to be large (133–446 Mha) (Canadell & Schulze, 2014; Deininger et al., 2011) and it can be exported to the EU. Considering crop residues, flexible supply of forestry biomass, and its trade, would increase supply to biomass markets for the bioeconomy and reduce their impacts, at least on EU food markets, but this is not taken into account in this study.
Furthermore, GHG mitigation effects of the chemical/material use of PBC biomass are not accounted for because the fossil resource-based chemical industry is not explicitly modeled. Chemical and material use of PBC and forestry biomass may potentially contribute to climate change mitigation by reducing GHG emission (Broeren, Kuling, Worrell, & Shen, 2017; Cok, Tsiropoulos, Roes, & Patel, 2014). If GHG mitigation effects of chemical/material use of biomass were considered, bioeconomy scenario impacts on agricultural markets, if defined by their GHG mitigation contribution, would be less than shown in our results because fewer amounts of biomass could be utilized in the energy sector to meet the GHG mitigation target. However, other targets in renewable electricity generation and renewable energy in gross end-use energy could still require similar levels of biomass feedstock. In addition, carbon mitigation effects of the chemical/material use of biomass vary significantly according to the source of biomass feedstock. In this regard, the potential to improve the analysis. Such analysis may involve the spatial dimension of marginal land availability and aim at the reconciliation with the spatial dimension of potential demand by processing plants. Furthermore, bioeconomy scenarios may include PBC production and demand not only in the EU, but also in global markets. The modeling of global biomass trade (including PBC and forestry biomass as well as intermediate products in the value chain) will support the understanding of potential bioeconomy market developments. Finally, GHG emission assessment should include not only direct emission changes of PBC based on its value chains but also its indirect impacts on agriculture and soils as well as substitution effects in energy and material production.

### 4.6 Summary and future research needs

We assessed future bioeconomy scenario impacts on agricultural markets in the EU and the ROW, using a coupled modeling system between ESIM and TIMES-PanEU. All bioeconomy scenarios show strong market impacts and direct land use change regarding the increase in total agricultural land use as well as substitution of crops and pasture by PBC. However, employing PBC (scenario “Bio_hi”) instead of food-based biomass (scenario “Bio_bau”) reduces increases in food prices. Bioeconomy scenarios and the sensitivity analyses show that innovations in agriculture and shifts toward a diet with less animal product consumption as well as crop yield improvement are options to mitigate increases in agricultural prices. However, pressures on land rents and additional land demand for food and nonfood crops are very likely to increase until 2050.

For future research, better data about marginal land availability and the opportunity cost of its use for PBC have the potential to improve the analysis. Such analysis may involve the spatial dimension of marginal land availability and aim at the reconciliation with the spatial dimension of potential demand by processing plants. Furthermore, bioeconomy scenarios may include PBC production and demand not only in the EU, but also in global markets. The modeling of global biomass trade (including PBC and forestry biomass as well as intermediate products in the value chain) will support the understanding of potential bioeconomy market developments. Finally, GHG emission assessment should include not only direct emission changes of PBC based on its value chains but also its indirect impacts on agriculture and soils as well as substitution effects in energy and material production.

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