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Downscaling of agricultural market impacts under bioeconomy development to the regional and the farm level—An example of Baden-Wuerttemberg

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Abstract

The expansion of the bioeconomy sector will increase the competition for agricultural land regarding biomass production. Furthermore, the particular path of the expansion of the bioeconomy is associated with great uncertainty due to the early stage of technology development and its dependency on political framework conditions. Economic models are suitable tools to identify trade-offs in agricultural production and address the high uncertainty of the bioeconomy expansion. We present results from the farm model Economic Farm Emission Model of four bioeconomy scenarios in order to evaluate impacts and trade-offs of different potential bioeconomy developments and the corresponding uncertainty at regional and farm level in Baden-Wuerttemberg, Germany. The demand-side effects of the bioeconomy scenarios are based on downscaling European Union level results of a separate model linkage between an agricultural sector and an energy sector model. The general model results show that the expanded use of agricultural land for the bioeconomy sector, especially for the cultivation of perennial biomass crops (PBC), reduces biomass production for established value chains, especially for food and feed. The results also show differences between regions and farm types in Baden-Wuerttemberg. Fertile arable regions and arable farms profit more from the expanded use of biomass in the bioeconomy than farms that focus on cattle farming. Latter farms use the arable land to produce feed for the cattle, whereas arable farms can expand feedstock production for new value chains. Additionally, less intensive production systems like extensive grassland suffer from economic losses, whereas the competition in fertile regions further increases. Hence, if the extensive production systems are to be preserved, appropriate subsidies must be provided. This emphasizes the relevance of downscaling aggregated model results to higher spatial resolution, even as far as to the decision maker (farm), to identify possible contradicting effects of the bioeconomy as well as policy implications.

1 | INTRODUCTION

Two major developments will affect the global resource balance and hence demand and supply of agricultural biomass. First, an increase in agricultural biomass demand. By 2050, the world population will have grown to over 9.7 billion people, which is equivalent to an increase of around 30% compared to 2017 (UN, 2017). Additionally, the enlargement of the global middle class is likely to increase demand for resources, based on more extensive household consumption (Imbert, Ladu, Morone, & Quitzow, 2017). Second, the world is being challenged by anthropogenic climate change and fossil-based resource consumption should decline (McGlade & Ekins, 2015). The substitution of fossil-based with bio-based resources is considered a major pillar of the transition of the current economy toward a more sustainable path; this is combined with increasing resource use efficiency by recycling and the cascade use of resources (D'Amato et al., 2017). While renewable raw materials have been used for human purposes for thousands of years, the focus in the recent bioeconomy discussion are innovative biomass value chains that comprise new material production technologies.

Agricultural biomass will play a major role in the transformation toward a bioeconomy and the agricultural sector is, therefore, likely to be affected strongly due to increasing competition of biomass for food, feed, energetic, and material uses. Bell et al. (2018), for example, estimate that the production of food and energy needs to increase by 50% until 2030 compared to 2010. In addition to the production of traditional agricultural biomass, the production of perennial biomass crops (PBC) on agricultural land, such as miscanthus and short rotation coppice, is likely to play a key role as feedstock for material production in the future (Olsson & Saddler, 2013). Thus, due to the increasing demand for biomass, there will be incentives to increase production in the already intensive agricultural sector of the European Union (EU) as well as to import additional biomass. However, an increase in intensity of agricultural production is likely to foster negative ecological impacts, because the current intensity level already imposes negative effects on the environment such as biodiversity loss (Hazell & Wood, 2008; Tsiafouli et al., 2015). The competition in usage for the limited agricultural land is where technology and economic models can help to understand the potential future effects of increasing biomass demand for energy and materials on markets and the environment. Linking simulation models at different aggregation

levels can support the evaluation of possible pathways toward the bioeconomy (Wicke et al., 2015).

There are already several studies that present linkages of simulation models to assess the bioeconomy. Mubareka et al. (2014) present a modeling framework to assess forest-based bioeconomy scenarios that consist of a partial equilibrium model for the forest sector, a forestry dynamics model for forest growth and harvest, and a wood resource balance sheet. Deppermann, Blesl, Boysen, Grethe, and Bruchof (2016) combine an energy system model with an agricultural sector model for impact analysis of the increasing use of biomass for energy at EU level. Furthermore, Lehtonen and Okkonen (2013) apply regional input–output modeling to the investigation of the socioeconomic impacts of a conventional, decentralized bioeconomy. This bioeconomy comprises wood as a building material and as a feedstock for bioenergy. Van Meijl et al. (2018) extend an economy-wide model with new bioeconomy sectors and use it side by side with a regional energy system model in order to evaluate new biomass value chains for the Netherlands. All these studies examined important aspects of possible bioeconomy pathways, but they lack in the effects at farm level. However, there are also two important model linkages that also take account of farm level. One of them is the well-developed integrated approach of the *SEAMLESS* model framework (van Ittersum et al., 2008). This model framework comprises, among other models, the farm model FSSIM and the agricultural sector model SEAMCAP. The model framework has been used for a wide range of impact assessments including some with a bioeconomy focus (Janssen et al., 2010; Louhichi et al., 2010). CAPRI, the basis of SEAMCAP, is a stand-alone approach also used separately without the integrated framework pathways. Wolf et al. (2015) combine the economic models FSSIM and CAPRI with a crop growth modeling framework and an environmental model for the nitrogen cycle in order to analyze the effects of climate change. The second model linkage is the *Thünen Modelling network* (Offermann et al., 2015) that comprises, among others, a farm model (FARMIS), a general equilibrium model (MAGNET), and a partial equilibrium model (AGMEMOD). Banse et al. (2016) use this modeling network to analyze bioeconomy pathways, comprising agricultural, wood, and energy markets. These last two model linkages show the necessity of combining models with different characteristics to cover the full range of effects of a bioeconomy expansion.

This is where we start our study and analyze possible bioeconomy developments. Hence, the advantage of this study is

the combination of two major components. First, the combination of models that simulate different bioeconomic sectors and the downscaling of EU level results to farm level. Second, the simulation of different bioeconomy scenarios with a wide coverage of parameters that comprise different technological and political developments. These scenarios aim to consider the high level of uncertainty of the technology development and policy framework conditions that accompany the bioeconomy expansion.

The specific objective of the study is an assessment of the effects of different scenarios of energetic and material use of biomass in the EU on agricultural production at the regional and farm level, with an example focus on different farm types and regions in the state of Baden-Wuerttemberg, Germany. As the EU is a large region and changes in the demand and supply of agricultural products have repercussions on international markets, and as there are strong interactions between the energy system and the agricultural system, we simulate different bioeconomy scenarios generated with an integrated network of an EU-wide energy sector model, Pan-European TIMES model (TIMES-PanEU), and a global agricultural sector model, European Simulation Model (ESIM). While this integrated model network is presented elsewhere (Choi et al., 2019), the study presented here focuses on the downscaling of agricultural market data at EU and country level to the farms in the German federal state of Baden-Wuerttemberg. This downscaling is based on the mapping of ESIM results to the agricultural farm model Economic Farm Emission Model (EFEM). The examined scenarios comprise four narratives that were developed in a working group of modelers from the *Bioeconomy Research Program Baden-Wuerttemberg* (https ://biooekonomie-bw.uni-hohenheim.de/en).

In the following, we present a method section first that explains the models used in this study and thereafter provide specific assumptions of the examined bioeconomy scenarios. This is followed by the presentation and discussion of the model results.

2 | MATERIALS AND METHODS

The demand for agricultural nonfeed and nonfood biomass has lately been dominated by the bioenergy sector. Hence, the development of the energy sector plays an important role in the evaluation of different transition paths. In order to implement this, a linkage between ESIM and the energy sector model TIMES-PanEU is performed. TIMES-PanEU is a disaggregated, bottom-up energy system model that minimizes the total discounted system costs, while considering different technologies and pathways of energy conversion (Blesl, Kober, Kuder, & Bruchof, 2012). The model covers all sectors connected to the energy supply and demand at country level. The model linkage is performed by an iteration process

with ESIM that results in a market equilibrium of biomass demand for energy (TIMES-PanEU) and agricultural biomass supply for energetic purposes (ESIM). Since the link between ESIM and TIMES-PanEU was developed elsewhere (Choi et al., 2019; for an earlier version, see Deppermann et al., 2016), it is not described here.

After the completion of the iteration process, resulting price changes for agricultural products are transferred to EFEM. EFEM then simulates the effects of the integrated scenarios, mediated through agricultural price changes, at farm and regional level. EFEM results are not fed back into ESIM, as agricultural production in Baden-Wuerttemberg is a relatively small region in comparison to Germany or even the EU, and therefore, deviations from the supply response of Germany in ESIM would not significantly affect agricultural prices. However, selected parameters, such as yield growth rates and abolishment of direct payments, were harmonized between EFEM and the Germany component of ESIM. The supply response of ESIM and EFEM to similar price changes was compared in initial test runs. This comparison shows only small differences of supply that mainly reflect special features of the agricultural sector of Baden-Wuerttemberg, such as unfavorable productions conditions for sugar beet in large parts. Figure 1 gives a schematic overview of the used models and the data transmissions between these models.

2.1 | European Simulation Model

European Simulation Model (Grethe et al., 2012) is a global agricultural sector model, which is able to calculate market equilibriums in biomass demand and supply with consideration of changes in population, income, dietary preferences, technology, and policies. It depicts single EU28 countries as well as Turkey and the West Balkan countries in detail regarding prices, animal feeding, acreage and yield, subsidies, and border policies. Remaining world regions are modeled at an aggregated level, the US and the Rest of the World (ROW), and without distinguishing between yield and area and coverage of agricultural policies. Base year data, which are used for model calibration, concerning production, consumption, processing, and acreage comes from the CAPRI database, Eurostat, and FAO. Commodity prices come from DG AGRI (2017). Agricultural supply and demand are modeled as isoelastic behavioral functions. For the EU28, the West Balkan countries, and Turkey, crop yields and area demand functions are distinguished in crop supply modeling. Crop yields change with respect to own crop price and technical progress parameters. We do not consider changes in input demand, for example, fertilizers, labor, and energy with respect to each input price in this study. Area demand changes with respect to variables of own and cross crop prices and land rent prices. For the US and ROW, crop supply is a function of global crop prices. Agricultural trade is modeled as a net
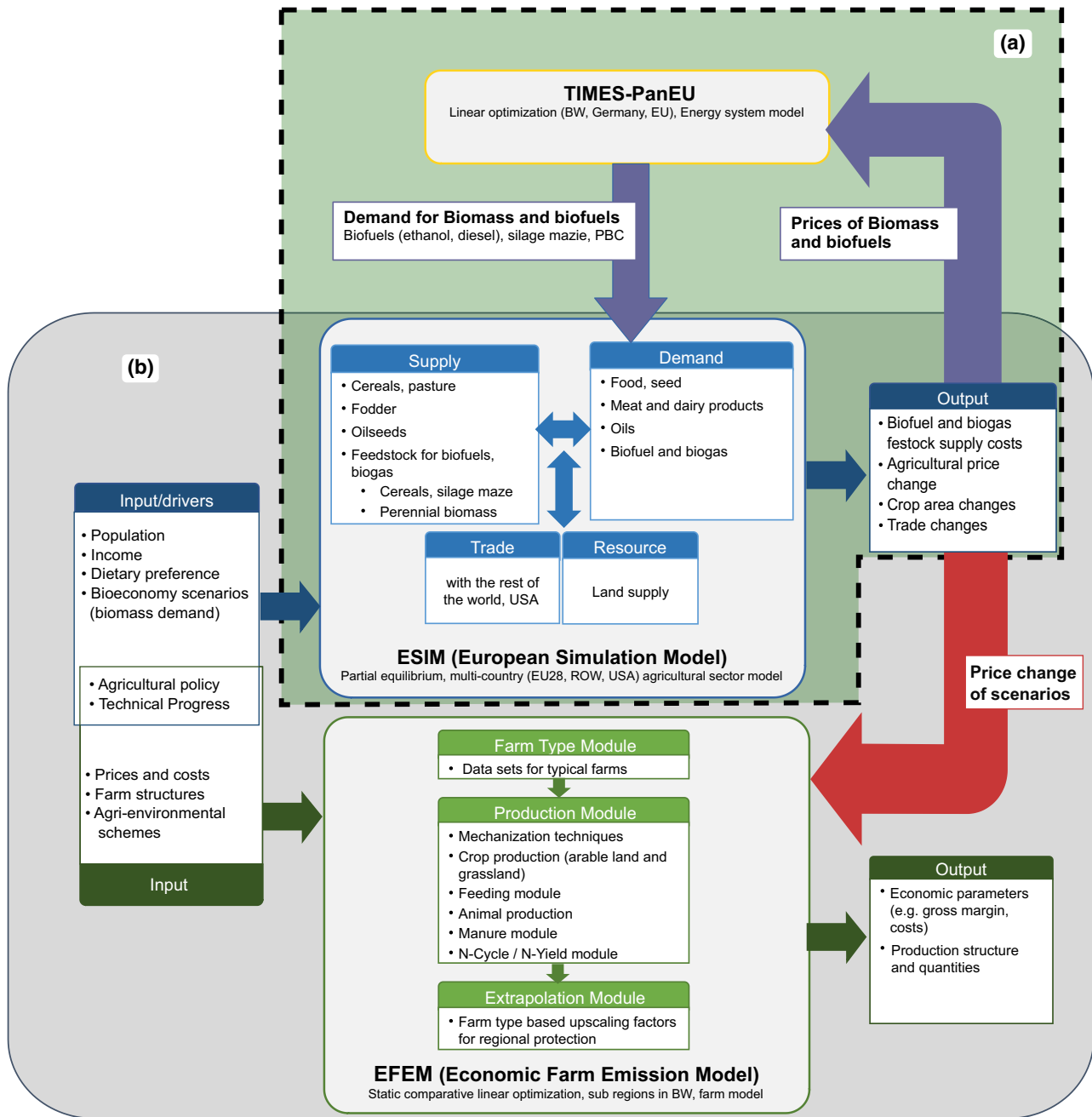
FIGURE 1 Schematic overview of the model linkage and contents of data transmissions. Part (a) shows the interaction between the agricultural sector model ESIM and the energy system model TIMES-PanEU (Choi et al., 2019). Part (b) depicts the model approach of this contribution

trade specification and the mechanism of price transmission with a change in the net trade situation is depicted based on a logistic functional form, accounting for tariff rate quotas, *ad valorem* tariffs, and specific tariffs.

Supply of PBC is explicitly modeled with assumptions on the technical diffusion of PBC in the agricultural area of the EU. PBC can be cultivated on land currently used for crops and permanent grassland in the EU or on land not under production previously. Restrictions for land use for PBC are a matter of scenario definition. Land demand for food and

nonfood biomass, that is, PBC, competes in a land market with a limited land endowment. Details about PBC supply modeling and agricultural land supply are given (Choi et al., 2019).
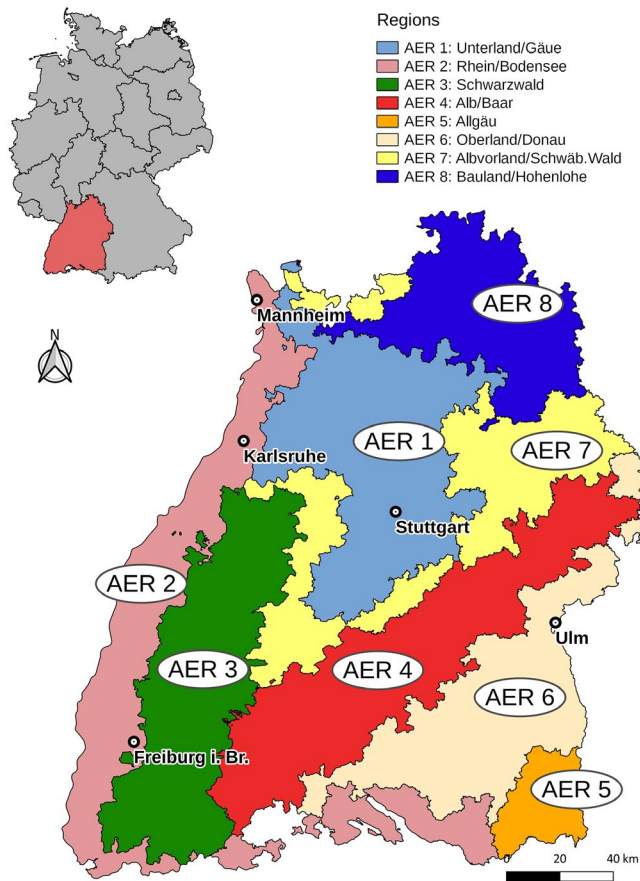
2.2 | Economic Farm Emission Model

Economic Farm Emission Model (Kazenwadel, 1999) is a comparative static linear optimization model and it computes farm management decision-making by maximizing the gross

margins of agricultural farms, while taking specific regional constraints into account. Regional constraints include arable land and grassland endowment, livestock numbers, and crop rotation limits due to agricultural and climate production conditions. Farm level results can be upscaled to regional levels by linear extrapolation. The regional level of EFEM consists of eight Agro-Ecological Regions (AER) in the federal state of Baden-Wuerttemberg (Figure 2). These regions are characterized by similar agricultural production conditions, such as geological, topographical, and climate conditions (Table 1). Although AER are on average five times larger than NUTS-3 regions (regional classification of the territory of EU; cf. EC, 2016), they are more suitable for application in the study region. AER have regionally differentiated own production conditions with own production foci. For example, there are **fertile crop farming regions (AER 1)**, regions with **extensive forage farming in low mountain ranges (AER 3), marginal low mountain regions with mixed farms (AER 4),** and regions with a more **intensive dairy production based on grassland (AER 5)**.

The model consists of three modules: farm type, production, and extrapolation. The farm type module contains the different farm structures in each region. Each region is

FIGURE 2 Study region (Baden-Wuerttemberg) within Germany and spatial resolution (AER) of Economic Farm Emission Model

TABLE 1 Climate/agricultural characteristics of the Agro-Ecological Regions (AER) in Baden-Wuerttemberg (LEL, 2018)

Agro-Ecological Regions	Unterland/ Gäue AER 1	Rhein/Bodensee AER 2	Schwarzwald AER 3	Alb/Baar AER 4	Allgäu AER 5	Oberland/ Donau AER 6	Albvorland/ Schwäb. Wald AER 7	Bauland/ Hohenlohe AER 8
Elevation (m)	100–400	100–650	300–1,000	600–1,000	600–900	500–800	400–700	150–600
Avg. annual temperature (°C)	8.0–>9.0	8.0–9.0	5.5–>7.0	6.0–7.5	6.0–7.5	7.0–8.0	6.5–8.0	6.5–8.0
Avg. annual precipitation (mm)	650–750	550–1,100	800–1,500	600–1,100	1,000–1,600	650–800	700–1,000	600–1,000
Soil quality index (Ackerzahl) (0–100)	40–>80	20–70	20–40	20–40	30–50	30–60	20–60	30–50
Agriculturally used area (EFEM) (ha)	221,872	170,222	95,379	215,399	43,000	240,812	172,813	177,667
Share of arable land (EFEM) (%)	81	76	17	55	12	68	50	82

represented by a maximum of six typical farm models, for example, dairy farms or arable farms that depict the most common farm types in the respective region. Each region can also be represented by several farm types of the same line of production (e.g., dairy farm) in different sizes. The general classification of these farm types is based on the farm typologies of the Farm Accountancy Data Network (FADN; EC, 2018). Sizes of a particular farm type per region are differentiated as well. The capacities of typical farm types are based on average single farm data from the FADN and farm capacities create restrictions for the optimization process.

The prices of products and means of production are given exogenously in EFEM. The considered costs include variable machinery costs and do not include any fixed costs, such as investment costs. The costs were obtained from public databases (KTBL, 2017; LEL, 2017b; 2017c).

The production module includes all relevant arable crops, grassland production systems, and husbandry types in Baden-Wuerttemberg. The arable crops include 16 crops, such as cereals and forage crops. These activities differ regionally in terms of yields and intensities. The intensities correspond mainly to the amount of fertilizer application. Furthermore, the crops can be combined with various regional environmental measures. The farms can also cultivate most of the crops either with conventional tillage (plough) or with conservation tillage (mulch-till). However, the farms are not allowed to plough up grassland to convert it to arable land due to policy restrictions (MLR, 2016). With miscanthus and short rotation coppice (SRC), two different types of PBC are integrated in EFEM. We assumed a 20 year cultivation period of both PBC and used average annualized costs for sowing, cultivation, harvesting, and recultivation. It takes 1 year to establish miscanthus and from then on it is harvested annually. SRC comprises poplar with a 4 year establishing period and a 4 year harvest interval. The yield is then converted to an annual average. Due to the small production quantity and the low prevalence of PBC, there is no comprehensive statistic available that includes prices for the different PBC. However, PBC are currently mainly used for heat production in Germany (FNR, 2018). Furthermore, we assume that the SRC wood chips have the same characteristics as forest wood chips and therefore used the prices for forest wood chips (C.A.R.M.E.N., 2018) in the base year. The price of miscanthus is based on LfL (2018), who derived it from the price of wood chips (28 €/MWh) and the heat value of miscanthus (17.6 MJ/kg). Additionally, the more difficult combustion handling of miscanthus and lower density that raise logistic costs are taken into consideration, which lowers the derived price by around 30% (LfL, 2018).

Currently, farmers are exposed to risks in adopting PBC due to the long cultivation period and lack of experience in cultivation. Hence, farmers request an additional premium on top of the market price to compensate for the occupation and risk. This willingness to accept (WTA) has been quantified based on a choice experiment with actual famers (Gillich, Narjes, Krimly, & Lippert, 2019) and is implemented in EFEM. The maximum cultivation area of PBC is restricted by regional cultivation conditions and environmental limitations (Kaule et al., 2011). In general, miscanthus not only achieves higher gross margins than SRC but also has higher requirements on climatic and crop production conditions.

Agricultural biogas substrate production (silage maize, grass silage from arable land and grassland, and whole crop silage of grain) is integrated in EFEM as a sales option with exogenously defined prices based on a survey of biogas plant operators (IER, 2013).

The extrapolation module is the third part of EFEM. In this module, the farm level results are projected onto the regional level of AER. The corresponding extrapolation factors are defined by a separate linear optimization approach for depicting the entire agricultural production in each region. The agricultural census of 2010 provides the relevant regional capacities for the projection to AER level. Schäfer (2006) describes this modeling approach in detail, and a more recent application of EFEM can be found in Schwarz-v. Raumer, Angenendt, Billen, and Jooß (2017), and Krimly, Angenendt, Bahrs, and Dabbert (2016). EFEM results are validated against the agricultural census of 2010 by comparing data on animal numbers, crop production, and land use with statistical data (Suple).

2.2.1 | Example farms

We expect that the impacts of bioeconomy scenarios differ not only in regions but also in farm types. Hence, we present the results of EFEM at farm level by selecting four farms that are representing the region as well as farm-type diversity. Table 2 shows the capacities of these farms. These capacities increase over time, due to structural change and technical progress. The first farm is an **arable farm** (**1AF**) that is located in the distinct cropping region (AER 1) and has no livestock production. The second farm, located in the black forest (AER 3), is a **dairy farm** that represents an **extensive production (3DF)**. The third farm is an **intensively managed dairy farm (5DF)** located in AER 5. This farm is characterized by a high livestock density per area. Both regions are characterized by grassland-based milk production. The fourth farm is a **pig farm (8PF)** and has additionally a relative high endowment of arable land. The farm is located in the northeast region of Baden-Wuerttemberg (AER 8). Those farm types and its typical agricultural production conditions can also found in other regions of Europe, and therefore, the results can help to highlight the possible effects of differently developed bioeconomy in other regions of Europe as well.

TABLE 2 Capacities of example farms in each year

Farm type	AER 1 (Unterland/Gäue)			AER 3 (Black forest)			AER 5 (Allgäu)			AER 8 (Bauland/Hohenlohe)		
	1AF	1AF	1AF	3DF	3DF	3DF	5DF	5DF	5DF	8PF	8PF	8PF
Year	2010	2030	2050	2010	2030	2050	2010	2030	2050	2010	2030	2050
Arable land (ha)	120	171	231	18	24	31	11	16	22	78	113	154
Grassland (ha)	10	14	19	70	91	115	70	88	109			
Other cattle (Animal capacity)				29	34	39	51	62	76			
Dairy cows (Animal capacity)				55	64	75	98	121	147			
Fattening bulls (Animal capacity)				7	8	9	7	9	10			
Suckler cows (Animal capacity)												
Fattening pigs (Animal capacity)										600	971	1,408
Sows (Animal capacity)										220	308	411

2.3 | Bioeconomy scenarios

We simulate four scenarios (Table 3), which were defined by a larger working group of modelers from the *Bioeconomy Research Program Baden-Wuerttemberg*. These scenarios comprise different potential futures of the bioeconomy. They share certain features, and they differ from each other regarding other features. Scenarios include a business as usual scenario (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-Wuerttemberg). No changes are assumed in biomass supply and demand functions in the world outside 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. While demand for the material use of biomass is increasing from BAU over BIO_mid to BIO_hi, the politically driven demand for energy from biomass declines. From BIO_mid on, there is no further use of 1G biofuels in transportation after 2030, and under the BIO_hi scenarios, no biogas is produced from agricultural products, only from biowaste. As an increasing demand for the material use of biomass puts pressure on the global biomass balance, a scenario is designed which combines the high demand for biomass under BIO_hi with a more sustainable consumption pattern in the EU (BIO_hi+diet). By 2050, the per capita demand for food staples in the EU is assumed to be 10% lower due to lower food waste rates, and for dairy products and meat, this decline in per capita demand is even greater, as in addition to the lower food

waste, per capita consumption also falls for these products. For an empirical foundation of scenarios with declining meat consumption without increasing staple food production, see Cordts (2015).

All scenarios rely on the same projections of income and population as demand drivers and technical progress in animal and plant production from exogenous sources (cf. Choi et al., 2019). In addition, all scenarios comprise compliance with political targets in energy and climate policy in Baden-Württemberg, Germany, and the EU. As wood production from forestry is not treated endogenously in any of the models, exogenous wood supply from forests is defined for BW, Germany, and the EU based on Mantau et al. (2010), Mantau (2012, 2015), and Thünen-Institut (2017). Furthermore, the material use of biomass is not modeled endogenously, and therefore, exogenous assumptions are made for the material use of wood and differ among scenarios. From BAU over BIO_mid to BIO_hi, material use of biomass is increasing. The individual scenarios are based on projections by Piotrowski, Essel, Carus, Dammer, and Engel (2015) and own assumptions. Thus, with a fixed supply of wood from forests and different exogenous assumptions on the material use of wood, the iterative solution of TIMES-PanEU and ESIM reflects a market equilibrium between energetic demand for woody biomass and supply of PBC from the agricultural system. The iterative solution considers exogenous supply and demand components as well as interactions with other components of the energy and the agricultural system.

After the iterative process between ESIM and TIMES-PanEU resulted in an equilibrium, each scenario has an individual set of prices for the different agricultural products. The changes of these prices compared to the base year are transferred to EFEM in order to define the prices under the different scenarios at Baden-Wuerttemberg level.

TABLE 3 Overview of bioeconomy scenarios

	BAU	Bio_mid	Bio_hi	Bio_hi+diet
Narrative	Business as usual, no strong development of material use	Expansion of innovative material use; no biofuels	Expansion of traditional and innovative material use; No biofuels; biogas only from waste	Bio_hi plus more sustainable food consumption
Features applying to all scenarios				
Land endowment of agriculture in BW	Decreasing arable land (−0.07%) and constant grassland area (linear regression of historical FADN data [last 30 years])			
Agricultural policy	First pillar of CAP subsidies and tariffs abolished before 2030			
Animal capacities and land endowment of farms in BW	Increase per farm over time depending on region (linear regression of historical FADN data [last 30 years])			
Technical progress	Specific growth rates for crops (yield) and animal sectors based on Alexandratos and Bruinsma (2012) and own estimations			
Cost development (annual growth rate for EFEM)	Linear regression of historical FADN data (last 30 years): machinery and paid labor input: 1.8%, seeds: 1.3%, pesticides: 1.5%, others: 1.3%			
Population and income	Population and GDP change based on (EC, 2013; EIA, 2013)			
Greenhouse gas mitigation measures	EU: ETS sectors −75% in 2050 compared to 2005; GER: overall −80% in 2050 compared to 1990; BW: overall −90% in 2050 compared to 1990			
Share of renewables in electricity generation	80% in 2050			
Share of renewables in gross end use energy	EU: 60% in 2050, GER: 60% in 2050, BW: 80% in 2050			
Biomass supply from forests	Exogenous supply is defined for BW, GER, and the EU based on Mantau et al. (2010), Mantau (2012, 2015), and Thünen-Institut (2017)			
Wood demand for paper	No change in BW, GER, and EU due to increase in recycling efforts			
Biomass trade	No trade of PBC and wood from forestry			
Features differing among scenarios				
Biomass in chemical, material uses (annual growth rates)				
Traditional use	No change	1.7%	2.0%	
Innovative chemical, material use	No change	5.5%	8.1%	
1G Biofuels in transport				
Min	10% share from 2020 on	10% share by 2020, 0% afterwards		
Max	No restriction	0% of 1G biofuels after 2030 in transportation		
Biogas electricity generation				
Min	EU: current levels; GER: decline following a decommissioning curve due to energy policy (EEG)[a]		Current level until 2030, banned afterwards except for biogas from waste	
Max	No restriction: limited by the economic environment		Trend until 2030, banned afterwards except for biogas from waste	
Dietary trends[b]	No change in preferences			Cereals, sugar, potato, eggs, plant oils (−10%), meat products (−41.1%), dairy products (−29.7%)[b]

Abbreviations: 1G, first-generation biofuel; BAU, business as usual scenario; BW, Baden-Wuerttemberg; ETS, European Union Emission Trading Scheme; EU, European Union; FADN, Farm Accountancy Data Network; GER, Germany.

[a]Reference scenario (REF) from Güsewell, Härdtlein, and Eltrop (2019); Energy policy: German Renewable Energy Act (EEG, 2017).

[b]Dietary changes take effect from 2015 on and stepwise results in the aggregate reduction rates by 2050.

As the focus of this analysis is on BW, the following paragraphs describe special features of the implementation of technical progress and structural change under all scenarios in EFEM. EFEM is a comparative static optimization model, and therefore, technical progress as well as structural change parameters have to be set exogenously for each simulation year. As a result, different model years differ in the factor endowment of available land and animal capacities at farm as well as at a regional level, depending on technical progress and development of the available agricultural area. Changes in farm structure have to be considered in projections, because economic impacts on individual farms strongly depend on farm size (Zimmermann, Heckelei, & Domínguez, 2009). Furthermore, structural change can affect the relative distribution of farm types within regions. The specific structural change in Germany has shown a linear development since the 1950s (BMEL, 2016), and therefore, it seems plausible to assume such linear development also for the modeled time period in this study. Therefore, we projected the historical development of farm size up to 2030 and 2050. This historical projection has shown increasing farm size with differences in arable land, grassland, and stable capacities. We projected these farm endowments for different farm types separately based on FADN data of the last 30 years. In accordance with ESIM, we assumed that the EU gradually reduces the first pillar of direct payment of EU agricultural policy (Choi et al., 2019).

The overall grassland area in Baden-Wuerttemberg is assumed to be constant due to the ban on ploughing up grassland. The overall arable land is declining because of the expansion of traffic and settlement areas. Structural change does not only comprise the growth of individual farms but also changes in the composition of overall plant and livestock production in Baden-Wuerttemberg. As EFEM uses an extrapolation approach to depict regional production, the change in regional capacities of livestock production in 2030 and 2050 must be included in separate extrapolation factors for each simulation year.

Beside the factor endowments, the biological performances of plant and animal production activities differ in different regions. The underlying technical progress in plant production contains the yield development for different crops, which is harmonized with ESIM (Table 4). This yield projection is in order of size of existing studies that use crop models and other methods to examine scenarios until 2050 (Angulo et al., 2013; Kanellopoulos, Reidsma, Wolf, & Ittersum, 2014; Wolf et al., 2015; Zimmermann et al., 2017). For grassland, we assumed a constant yield justified by the constant historical yield development in Germany (DESTATIS, 2017). The biological performance of livestock production in the FADN data has shown a constant linear increase over the last 30 years in Baden-Württemberg. For this reason, we implemented annual growth rates for the different livestock sectors based on the trend of the last 30 years. These growth rates define the biological performance of different animals (e.g., piglets per sow, milk yield per cow) by 2030 and 2050.

TABLE 4 Yield projection of different crops compared to base year 2010 in EFEM (based on Alexandratos & Bruinsma, 2012)

	2030	2050
Cereals	+17%	+38%
Corn	+29%	+68%
Silage maize	+35%	+81%
Clover grass	+0%	+0%
Oilseeds	+35%	+81%
Sugar beet	+22%	+49%
Potatoes	+32%	+74%
PBC	+13%	+27%

Abbreviation: PBC, perennial biomass crops.

2.4 | Sensitivity analysis

In order to consider the high level of uncertainty in the development of the bioeconomy and the assumed framework conditions, we perform sensitivity analyses with respect to cultivation of PBC on grassland, the PBC price, and future yield levels.

2.4.1 | Effects of cultivation of PBC on grassland

The policy framework regarding permanent grassland protection is very strict and there are no indications that this will change in the near future. The time horizon of our simulation period, however, is quiet long, and therefore, a change in the according policy framework is possible. Therefore, we modeled all scenarios for 2050 again separately allowing the cultivation of PBC on grassland. The maximum cultivation of PBC on grassland, like PBC cultivation on arable land, is restricted by regional cultivation conditions and environmental limitations, which are defined separately for grassland and arable land by Kaule et al. (2011).

2.4.2 | Effects of a reduced PBC price

The decision of the farms to cultivate PBC depends on the producer price. The price development strongly depends on developments in technology, which are highly uncertain. Therefore, a sensitivity analysis with respect to the PBC price is necessary in order to evaluate the robustness of the results. In this sensitivity analysis, we lower the price of PBC by 20%, 40%, and 60% in order to see the effects of lower PBC prices on production. Other prices and parameters remain unchanged in this analysis.

2.4.3 | Effects of climate change-based yield changes

The simulation results are strongly driven not only by the modeled price changes of the iteration between ESIM and

TIMES-PanEU but also by the yield developments over the projection horizon. Therefore, it is important to consider the uncertainty of the yield development caused, for example, by climate change (Knox, Daccache, Hess, & Haro, 2016). In order to consider this uncertainty, we used yield changes from the ExpertN-Gecros model and applied them to winter wheat, winter rapeseed, and maize. The model was used in the research group "Agricultural Landscapes under Global Climate Change—Processes and Feedbacks on a Regional Scale" (FOR1695) of the German Research Foundation (DFG). As climate forcing for ExpertN-Gecros, daily data were used from the model coupling MPI_CLM_rcp85 as part of the ReKliEs-De-ensemble "Regional Climate Projections Ensemble for German" (Hübener et al., 2017). Regarding the temperature signal, MPI_CLM_rcp85 represents a medium scenario out of

the "continue-as-before"-family of the ReKliEs-De-ensemble. This sensitivity analysis is performed for crop farming region AER 1 and low mountain region AER 6. Table 5 shows the corresponding yield effects caused by climate change in 2050.

3 | RESULTS

First, we show price developments in bioeconomy scenarios. Second, we present the development of the agricultural sector under the BAU scenario compared to the base year in 2010. We start with the results for Baden-Wuerttemberg as a whole and proceed with the example farms. Third, we present the results of the bioeconomy scenarios compared to the BAU scenario in 2030 and 2050. Again, we start with the aggregated results for Baden-Wuerttemberg and close with the results of the example farms. Fourth, the last subsection supplements the results with sensitivity analyses.

3.1 | Price developments in bioeconomy scenarios

Table 6 presents the prices for agricultural products in the base year (statistics) and the price changes under bioeconomy scenarios compared to the base year resulting from the iterations between ESIM and TIMES-PanEU. The simulation results for

TABLE 5 Yield effects caused by climate change in example regions of Baden-Wuerttemberg in 2050 important crops. Yield changes are based on ExpertN-Grecos modeling (Knox et al., 2016)

	AER 1	AER 6
Wheat	−9.5%	−11.9%
Silage maize	−10.4%	+0.3%
Corn	−2.4%	+0.6%
Rapeseed	−1.1%	−6.4%

Abbreviation: AER, Agro-Ecological Regions.

TABLE 6 Prices for agricultural products in Baden-Wuerttemberg in base year (based on statistic) and modeled price effects of ESIM in different bioeconomy scenarios as base for scenario modeling in EFEM

	Base year (2010)		BAU		BIO_mid		BIO_hi		BIO_hi+diet	
	Unit	Price	2030	2050	2030	2050	2030	2050	2030	2050
Wheat	€/FM dt	15.1	29%	58%	27%	53%	28%	54%	25%	47%
Barley	€/FM dt	13.6	24%	55%	23%	57%	25%	60%	21%	49%
Corn	€/FM dt	15.3	−2%	16%	−3%	17%	−3%	18%	−5%	12%
Triticale	€/FM dt	13.7	31%	69%	30%	73%	32%	81%	27%	65%
Oat	€/FM dt	14.1	−29%	−17%	−31%	−18%	−30%	−17%	−32%	−22%
Sugar	€/FM dt	3.5	−53%	−53%	−55%	−55%	−55%	−55%	−55%	−56%
Potatoes	€/FM dt	14.7	32%	18%	31%	20%	38%	28%	30%	12%
Rape seeds	€/FM dt	33.5	16%	45%	15%	56%	6%	37%	5%	33%
Soy meal[a]	€/FM dt	33.3	22%	45%	21%	45%	24%	50%	20%	41%
Silage maize[b]	€/FM dt	2.8	−5%	28%	−4%	24%	−2%	−100%[c]	−6%	−100%[c]
Fodder[c]	€/FM dt	2.5	−50%	−29%	−48%	−27%	−45%	−100%[c]	−47%	−100%[c]
Miscanthus	€/DM dt	9.6	−8%	88%	19%	94%	42%	101%	39%	92%
SRC	€/DM dt	11.3	−8%	88%	19%	94%	42%	101%	39%	92%
Milk	€/kg	0.29	−2%	−1%	−2%	−1%	−2%	−2%	−4%	−6%
Beef	€/kg	3.31	−30%	−15%	−30%	−15%	−30%	−15%	−33%	−22%
Pork	€/kg	1.45	13%	36%	13%	37%	13%	37%	8%	24%

Abbreviations: EFEM, Economic Farm Emission Model; ESIM, European Simulation Model; SRC, short rotation coppice.
[a]Only purchase for feed.
[b]Price only for sale as biogas substrate.
[c]No biogas production with agricultural feedstocks (scenario assumption for EFEM).

prices generally show increasing trends in agricultural products, which are caused by increasing demand for food products due to population growth and higher income and substitution of food crops with nonfood biomass for the bioeconomy. Some products, however, have declining prices, such as beef and sugar, as a result of assuming market liberalization in the EU in the scenarios. PBC have the highest increase in prices among crops. Price increases in PBC can be explained by high PBC demand for the bioeconomy compared to land supply for PBC in ESIM. The prices for biogas feedstocks in 2050 in BIO_hi scenarios are defined to decrease by 100%. This is a necessary assumption in EFEM, because silage maize and fodder are produced either as nontradeable feed for own livestock or as biogas feedstock for sale. The on-farm use as feed has no sale price and the sale of biogas feedstock is no longer possible in BIO_hi due to scenario assumptions.

3.2 | Temporal effects in Baden-Wuerttemberg

In the following, the results of BAU scenario in 2030 and 2050 are compared with the base year in order to highlight the temporal effects. Figure 3 shows the composition of cultivated areas of arable crops in Baden-Wuerttemberg as a whole and the gross margin per utilized agricultural area (UAA) in the base period and in the BAU scenario in 2030 and 2050. The available agricultural cultivation area decreases because of the expansion of transport infrastructure and settlement areas. The cereal area slightly decreases by 3,000 ha and PBC increases to 61,000 ha until 2030. Sugar beet production almost
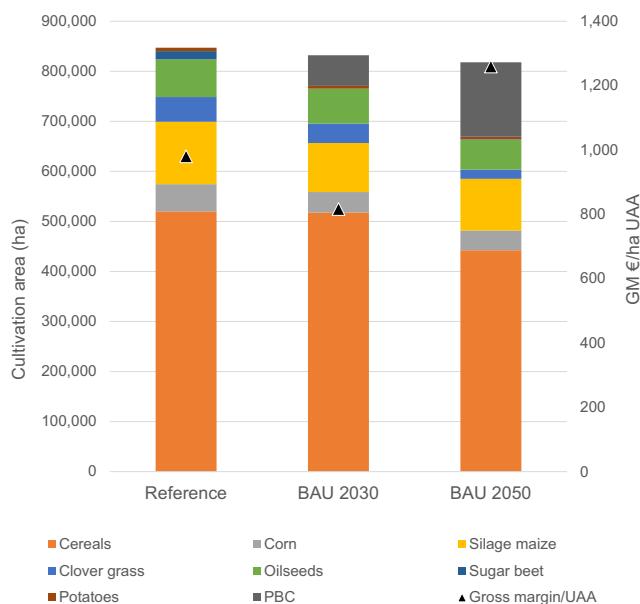
FIGURE 3 Comparison of base year (2010) with business as usual scenario (BAU; 2030 and 2050) in terms of cultivated arable crops and gross margin (GM) per utilized agricultural area (€/ha UAA) at Baden-Wuerttemberg level. PBC, perennial biomass crops

**TABLE 7** Comparison of livestock production in the base year 2010 with BAU scenarios in 2030 and 2050

	Base year	BAU 2030	BAU 2050
Produced milk (1,000 t)	2,632	3,066	2,986
Dairy cows (Animal capacities)	375,999	355,719	309,628
Suckler cows (Animal capacities)	52,302	3,744	4,277
Fattening bulls (Animal capacities)	115,521	4,576	7,677
Other cattle (Animal capacities)	261,300	206,950	179,252
Sows (Animal capacities)	248,744	253,475	206,573
Fattening pigs (Animal capacities)	1,166,117	1,226,627	1,390,076

completely vanishes by 2030 because of the abolishment of EU sugar market protection. The highest absolute area reduction is for silage maize with −27,000 ha (−21%) and it is mainly driven by a decrease in price of silage maize. The cultivation areas of the other crops also decrease. By 2050, the cultivation area of all crops but PBC is also lower than the area in the base period. This is caused by the substantial expansion of PBC, nearly 150,000 ha. Cereal production decreases the most by −78,000 ha (−15%). The cultivation areas of oilseeds, corn, and silage maize decrease by 15,000–21,000 ha compared to the base period. The gross margin declines from 980 to 836 €/ha in 2030. This is mainly caused by declining prices of important products in Baden-Wuerttemberg (milk, beef, and maize) due to agricultural policy reform related to market liberalization. The modeled price effects until 2050 result in a significant increase in the gross margin to 1,328 €/ha, due to a positive producer price development. The increase in the gross margin occurs despite consideration of the increased cost of machinery and production supplies.

The effects of the scenarios on livestock production are presented in Table 7. The projected decline in the beef price would lead to an almost complete reduction in suckler cow production and bull fattening. The number of dairy cows declines in Baden-Wuerttemberg over time, while milk production is higher than in the base period. In the period between 2030 and 2050, the increasing productivity is overcompensated for by the reduction in the number of milk cows, which results in a slight decrease in overall milk production in 2050 compared to 2030. The number of sows increases until 2030 and then decreases until 2050, because the cost of sow management rises more than the modeled proceeds. The increased productivity in pig farming causes an expansion of pig fattening.

3.3 | Temporal effects at farm level

Figure 4 shows the cultivated agricultural area and the gross margin of the example farms in the base year and in the BAU scenario in 2030 and 2050. All four example farms are characterized by a growth in land endowment and livestock farms of animal capacities, due to structural change and technical
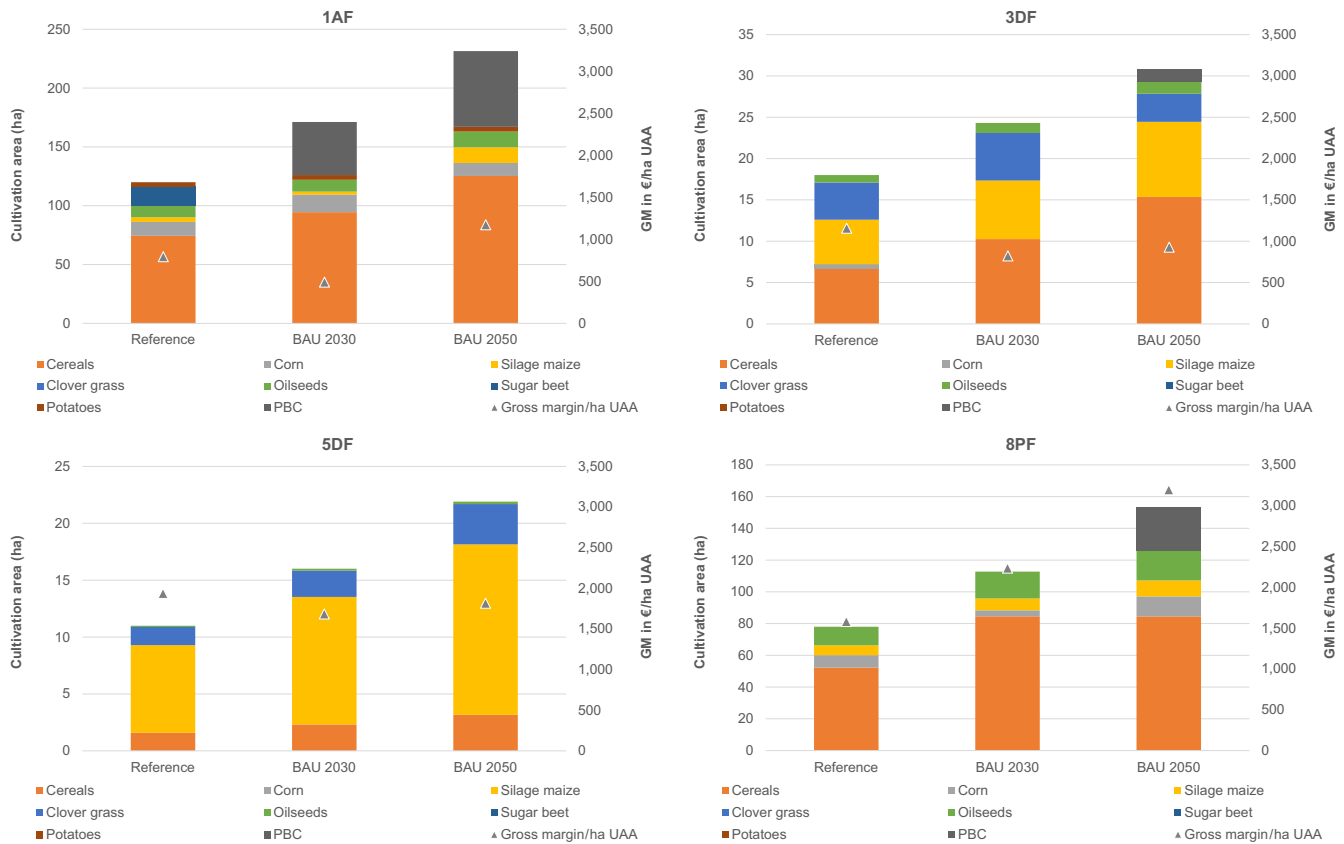
FIGURE 4 Comparison of cultivation area and area-related gross margin (GM) of example farms between base year scenario (2010) and business as usual scenario (BAU) scenario in 2030 and 2050. 1AF, arable farm; 3DF, extensive dairy farm; 5DF, intensive dairy farm; PBC, perennial biomass crops; 8PF, pig farm

progress. The example farms have different adoption strategies of crop rotation to the changed framework conditions over time, which also results in differences in the area-related gross margin. In 2050, all farms except the intensive dairy farm (5DF) cultivate PBC.

The arable farm (1AF) is the only farm that produces sugar beet in the base year, but discontinues production in the BAU scenario, due to the price drop that is caused by the reduced sugar market protection. PBC cultivation replaces the complete sugar beet cultivation and reduces the share of cereal cultivation in the farms' crop rotation in 2030. In 2050, the price development leads to the substitution of corn by silage maize, without changes in the overall crop rotation. The farm cultivates the largest area of PBC with 64 ha and with 28% of arable land also the largest share in 2050. The area-related gross margin of the arable farm reduces until 2030, which is caused by the price decline in import arable crops like sugar beet and silage maize for biogas production, which cannot be compensated for by the increasing prices of cereals and the expansion of PBC cultivation. The price increase in all major arable crops, especially the high increase of PBC by 2050, lead to an increase in the gross margin of almost 50% (1,173 €/ha) compared to the base year.

The extensive dairy farm in the Black Forest (AER 3) does not significantly change the crop rotation until 2030. In 2050, the farm reduces clover grass production, and hence, the high share of forage crops (silage maize and clover grass) in the crop rotation decreases from 55% to 39% compared to the base period. Clover grass area is substituted by cereals and corn, and the cultivation of PBC is expanded to 5%. Unfavorable production conditions for PBC in this region prevent further expansion. The considered price and yield developments result in a part substitution of clover grass for cereals in the feed composition for dairy cows. By 2050, the gross margin is 20% below the base year scenario. This farm suffers from the negative price developments on the beef market. Furthermore, it is only able to cultivate a small area of PBC and benefit only slightly from the PBC upsurge. The extensive dairy production is also sensitive to price changes in milk, because the farm cannot sufficiently compensate for the price decline in milk by increased productivity.

The intensive dairy farm in AER 5 (5DF) uses about 85% of its arable land to produce forage and the rest for cereal production. The farm expands the crop areas in the BAU scenario without changing the composition. It has the highest gross margin per ha in the base year, decreasing by 6% until 2050 to the second highest value. However, the margin

in 2050 is smaller than in reference. The decrease in the gross margin is similar to the extensive dairy farm, mainly driven by the unfavorable development of the price for beef and milk.

Like the dairy farms, **the pig farm in AER 8 (8PF)** does not cultivate PBC in 2030. However, the farm expands the cereal production while lowering the share of maize production. This effect is caused by increased comparative advantages of cereals, due to a price decrease for maize (corn and silage maize). By 2050, the farm cultivates PBC on 18% of its arable land, mainly at the expense of cereal production. The pig farm has a lower area-related gross margin than the intensive dairy farm in the base year, but it can double the gross margin by 2050 because of a strong increase in the profitability of pork production due to the price increase in pork and a relatively high productivity increase. As a result, the farm has the highest area-related gross margin of the example farms (3,195 €/ha).

3.4 | Impacts of the bioeconomy scenarios on agriculture in Baden-Wuerttemberg

3.4.1 | Changes in arable crop area and gross margin in Baden-Wuerttemberg

The impacts of the bioeconomy scenarios on the cultivation area of the main agricultural crops and the gross margin at Baden-Wuerttemberg level are presented in Figure 5. The biggest effect is caused by the expansion of PBC cultivation in most scenarios. This expansion comprises 60,000 ha in the BIO_mid 2030 scenario and increases to almost 90,000 ha in the BIO_hi 2030 scenarios compared to BAU. The comparatively large price increase in PBC by 2050 leads to an expansion up to the maximum cultivation limit of PBC of almost 150,000 ha in all scenarios. This corresponds to 19% of arable land in Baden-Wuerttemberg and is hence in accordance with ESIM results for Germany that simulate between 16% and 26% depending on scenario in 2050. This expansion replaces at most about 60,000 ha of cereal production in the BIO_hi scenario, which is the largest absolute decline in the different crops. Maize and oilseed cultivation areas also decrease with a more expanded bioeconomy until 2030, whereas the change in diet has no significant effect on arable crop areas. The permanent grassland plays, alongside arable land, a major role in the agricultural production of Baden-Wuerttemberg, but is distinguished by the assumed ban on ploughing and hence the limited usage options (feed and biogas feedstock). This characteristic results in the nonuse of 15% of the grassland in Baden-Wuerttemberg in 2050. This grassland is not in use, due to the productivity increase in livestock production and the decline in cattle production together with no other profitable utilization option.

In general, the area-related gross margin increases with a more expanded bioeconomy, up to +9% in BIO_hi at
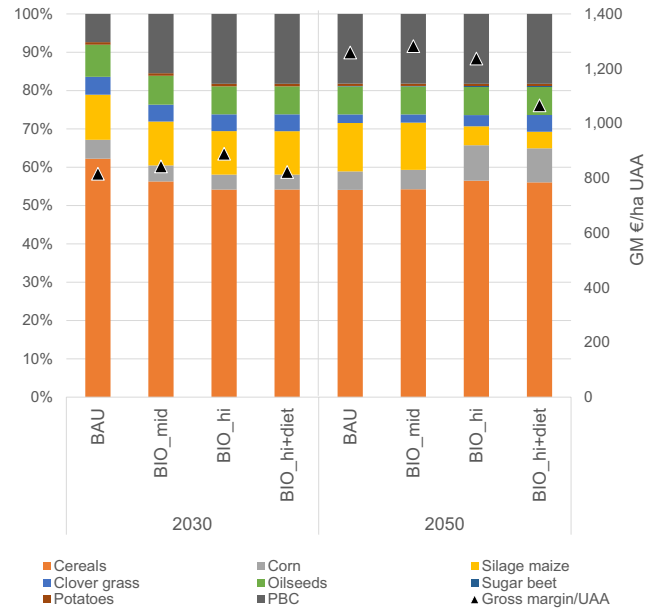

FIGURE 5 Impacts of the bioeconomy scenarios on arable crop areas and gross margin (GM) per utilized agricultural area (UAA) in Baden-Wuerttemberg. PBC, perennial biomass crops

Baden-Wuerttemberg state level in 2030. By 2050, the gross margin increases by almost 2% in BIO_mid compared to BAU, because the increased use of biomass for energy and materials causes higher prices for most agricultural products. The discontinued use of agricultural biomass for biogas and 1G biofuels in BIO_hi lead to a decline in rapeseed and silage maize prices, which reduces the gross margin by almost 2%. With a change in diet (BIO_hi+diet), the gross margin decreases because the increase in prices of major agricultural crops is offset by the price-reducing effects of the change in meat consumption and the area-related profitability decreases by 14% compared to the BAU.

3.4.2 | PBC cultivation in AER

The cultivation area of PBC varies strongly between the different regions (Figure 6). The focus of miscanthus cultivation is in fertile agricultural regions such as AER 1. The cultivation of SRC cannot compete in such regions. SRC cultivation, however, is more competitive in regions with less favorable arable production conditions, which explains the higher cultivation area of SRC in AER 3, AER 5, and AER 6. In the BAU scenario, the area for PBC ranges from no cultivation in the Swabian Alps (AER 4) to over 50,000 ha in the center of Baden-Wuerttemberg (AER 1) in 2050, which corresponds to 28% of arable land. AER 6 cultivates PBC on more than 35,000 ha. AER 4 has no cultivation of PBC due to restrictive environmental and climate limitations.

AER 3 and AER 5 show small absolute and relative PBC cultivation areas in Baden-Wuerttemberg over all scenarios. These regions have a relatively low endowment of arable land
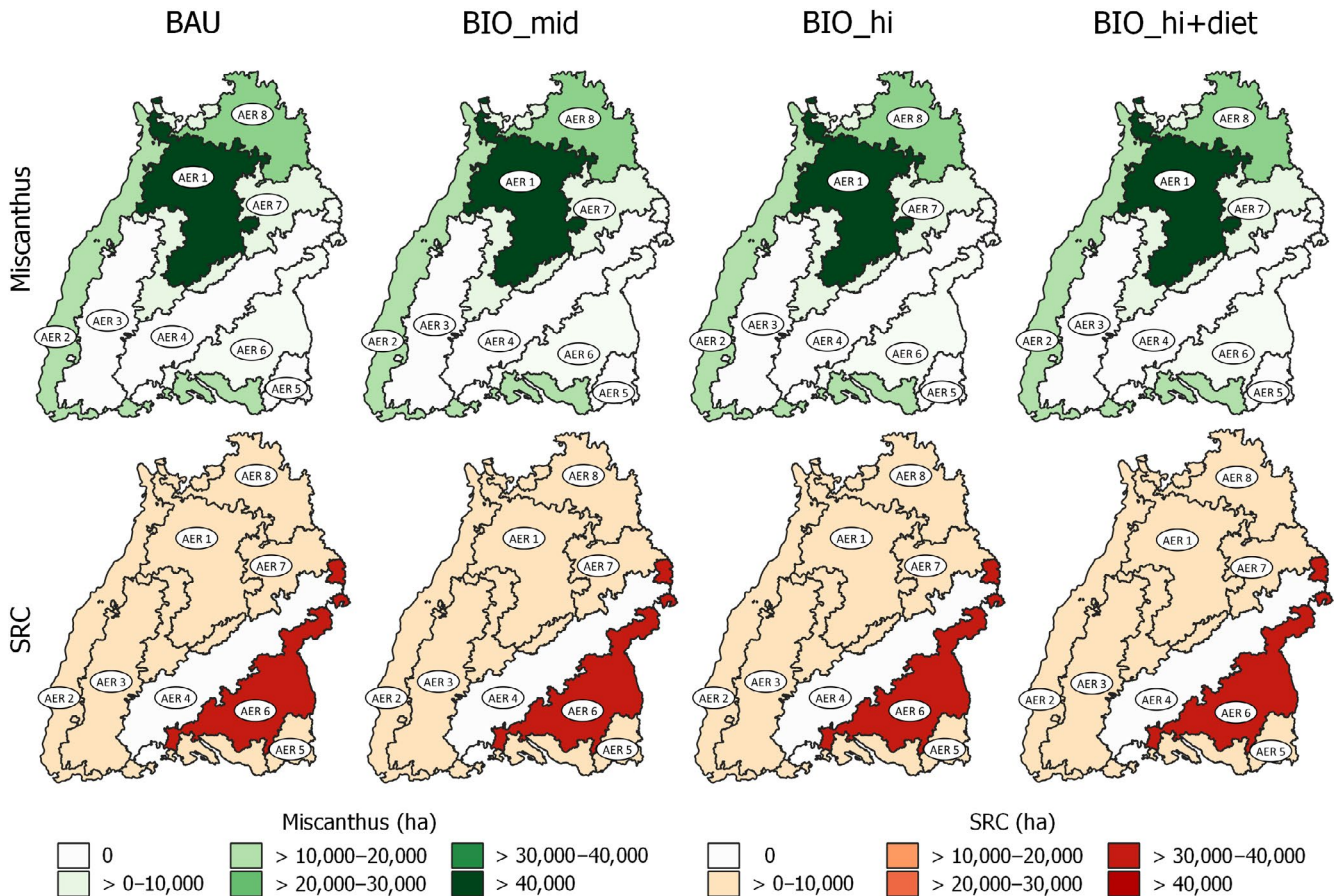
FIGURE 6 Cultivation area of miscanthus and short rotation coppice in 2050 per scenario and region in hectare

that could be cultivated for PBC, due to unfavorable production conditions. This limits the possible maximum cultivation area. Furthermore, livestock farms in these regions are strong competitors for PBC, and therefore, most of the land is used for feed production.

At Baden-Wuerttemberg level, the nonuse of agricultural biomass for biogas in BIO_hi strongly affects land use for the production of agricultural biomass for solely energetic and material use (silage maize for biogas and PBC), which decreases from 27% in BAU to 18%. The silage maize is mainly substituted by corn in fertile arable cropping regions such as AER 1 and tends to be replaced more frequently by cereal production in marginal regions (such as AER 5).

3.4.3 | Effects of bioeconomy scenarios at farm level

Figure 7 shows the impacts of the BAU as well as the bioeconomy scenarios on the crop cultivation and area-related gross margin of the different example farms. All farms have in common a reduced area-related gross margin in the scenario with the changed diet (BIO_hi+diet), which is around 10% for the arable farm and both dairy farms, but the different farm characteristic also caused different adoption strategies.

The **arable farm (1AF)** has no significant change in crop rotation in 2030. The PBC cultivation area does not change between the bioeconomy scenarios, because the cultivation is already very competitive with other crops due to the comparatively low price in the BAU scenario. In 2050, the farm only reduces the cultivation of silage maize in BIO_hi scenarios due to the banned use of agricultural biomass for biogas production. The farm uses the released area to expand corn production. The arable farm benefits the most, in relative terms, from the expanding bioeconomy. The gross margin increases by up to 4% in BIO_mid and 3% in BIO_hi compared to BAU in 2050. Although the farm has no livestock production, the gross margin also declines in BIO_hi+diet. This is because the changed diet also leads to declining feed prices. However, the effect is less pronounced than for livestock products, and therefore, the decline in the gross margin is the smallest of the example farms at −9%.

The **extensive dairy farm (3DF)** has no significant change in gross margin in 2030, and in 2050, the expanding bioeconomy has a slightly negative impact on profitability, as the gross margin declines by 3% in BIO_hi. The small expansion of PBC does not compensate for the higher feed costs for the farm, but the price developments change the comparative advantage of crops in the feed mix of dairy cows. Therefore,
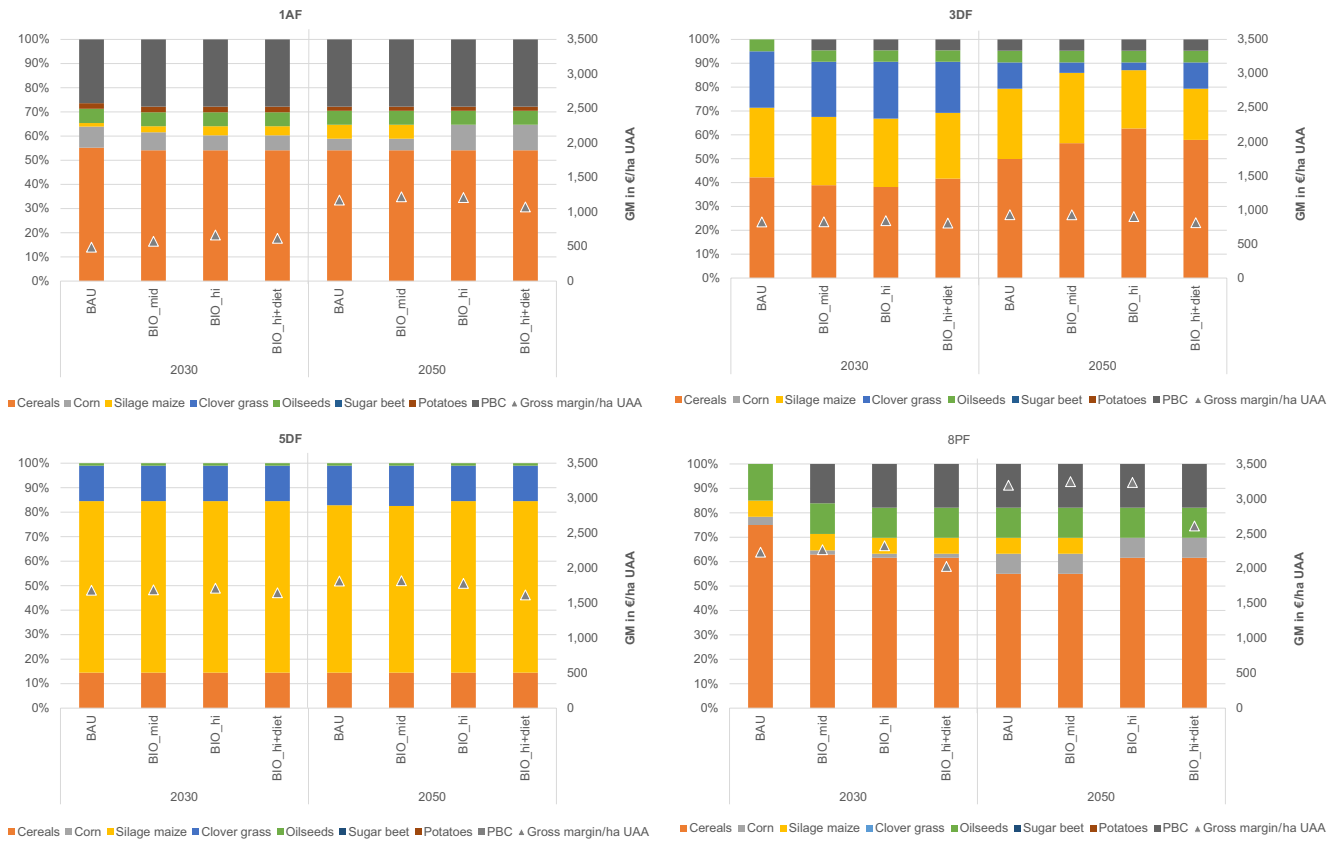
FIGURE 7 Impacts of the bioeconomy scenarios on cultivated arable crops and gross margin (GM) per utilized agricultural area (UAA) of example farms (1AF: arable farm; 3DF: extensive dairy farm; 5DF: intensive dairy farm; 8PF: pig farm). PBC, perennial biomass crops

with an increased bioeconomy, the farm substitutes clover grass by cereal and switch back in BIO_hi+diet. The gross margin in this scenario is additionally 10% lower than in the scenario without a change in diet.

The **intensive dairy farm (5DF)** does not change production on arable land, which highlights that dairy production is the most profitable production, regardless of the scenario. The farm uses the entire arable land for feed production and the milk price significantly changes only in the BIO_hi+diet scenario. Therefore, the gross margin is significantly lower only in the scenario with changed diet with −4% in 2030 and −9% in 2050.

The **pig farm (8PF)** benefits from the positive market developments in pork and, in contrast to the dairy farms, is able to profit from PBC cultivation due to the high endowment of arable land. The pig farm cultivates PBC in all bioeconomy scenarios in 2030. PBC prices reach a competitive level at higher prices than in BAU scenario, which differs from the arable farm. In 2050, the farm produces cereals on the arable land on which silage maize was grown as feedstock for biogas. The area-related gross margin of the pig farm increases by around 1.5% in the bioeconomy scenarios and at −19% has the highest decline due to changed diet. However, it is still the highest of the example farms.

3.5 | Sensitivity analyses

3.5.1 | Effects of cultivation of PBC on grassland

In the following, we compare the results with and without PBC cultivation on grassland in 2050 in order to analyze a possible change in the policy framework. The cultivation area of PBC on grassland does not differ between the scenarios and is 76,000 ha in Baden-Wuerttemberg (Table 8). The utilization of grassland shows no significant difference between BAU and BIO_mid. In both scenarios, there would still be 8% unused grassland, because the cultivation could not be unreservedly expanded due to ecological and environmental limitations. In both BIO_hi scenarios, however, the utilization of grassland to produce biogas feedstock is not an option anymore, and therefore, the share of unused grassland increases to 23%. In the scenarios in which PBC cultivation is allowed on grassland, the overall PBC cultivation area shows no difference between the bioeconomy scenarios. Because of the high comparative advantage to the other usage of grassland, the farms cultivate PBC already in the BAU scenario at the upper cultivation limit. Hence, the share of unused grassland in BIO_mid decreases to the same level (8%), whereas in BIO_hi, the share of PBC cultivation

TABLE 8 Comparison of use of grassland (ha) of different bioeconomy scenarios with and without cultivation of PBC on grassland per AER and Baden-Wuerttemberg (BW) in 2050

AER	Grassland use	No PBC on grassland				PBC on grassland			
		BAU	BIO_mid	BIO_hi	BIO_hi+diet	BAU	BIO_mid	BIO_hi	BIO_hi+diet
1	Feed	13,828	13,808	19,387	19,037	11,708	11,680	17,262	17,194
	PBC	0	0	0	0	7,175	7,175	7,175	7,175
	Biogas	15,530	15,530	0	0	13,533	13,533	0	0
	Unused	6,803	6,822	16,773	17,123	3,745	3,772	11,723	11,791
2	Feed	15,291	15,020	19,999	19,476	15,228	15,000	19,967	19,439
	PBC	0	0	0	0	5,135	5,135	5,135	5,135
	Biogas	12,301	12,301	0	0	11,177	11,177	0	0
	Unused	7,561	7,832	15,155	15,678	3,614	3,842	10,052	10,579
3	Feed	46,079	45,597	57,637	56,909	43,079	42,554	55,195	55,132
	PBC	0	0	0	0	5,322	5,322	5,322	5,322
	Biogas	12,895	12,895	0	0	12,895	12,895	0	0
	Unused	10,727	11,209	12,065	12,793	8,406	8,931	9,185	9,248
4	Feed	52,446	52,446	69,928	69,851	50,482	50,482	67,967	67,894
	PBC	0	0	0	0	3,002	3,002	3,002	3,002
	Biogas	24,453	24,453	0	0	24,043	24,043	0	0
	Unused	8,284	8,284	15,255	15,332	7,657	7,657	14,214	14,288
5	Feed	28,128	28,128	29,824	30,139	17,441	17,419	18,199	18,199
	PBC	0	0	0	0	14,872	14,872	14,872	14,872
	Biogas	4,943	4,943	0	0	758	780	0	0
	Unused	0	0	3,247	2,931	0	0	0	0
6	Feed	46,143	46,274	55,684	55,896	35,944	36,014	40,930	40,934
	PBC	0	0	0	0	20,374	20,374	20,374	20,374
	Biogas	8,847	8,786	0	0	5,239	5,239	0	0
	Unused	7,791	7,721	7,097	6,885	1,224	1,154	1,477	1,473
7	Feed	38,247	39,377	45,071	44,861	35,772	37,148	42,226	42,042
	PBC	0	0	0	0	12,817	12,817	12,817	12,817
	Biogas	13,252	13,252	0	0	12,551	12,330	0	0
	Unused	19,223	18,093	25,650	25,860	9,582	8,427	15,679	15,863
8	Feed	19,350	19,475	24,512	24,559	14,659	14,659	18,808	18,808
	PBC	0	0	0	0	7,914	7,914	7,914	7,914
	Biogas	4,258	4,258	0	0	4,258	4,258	0	0
	Unused	3,748	3,623	2,843	2,796	525	525	633	633
BW	Feed	259,512	260,126	322,042	320,729	224,312	224,956	280,554	279,643
	PBC	0	0	0	0	76,610	76,610	76,610	76,610
	Biogas	96,478	96,417	0	0	84,454	84,255	0	0
	Unused	64,139	63,586	98,086	99,400	34,753	34,308	62,964	63,875

Abbreviations: AER, Agro-Ecological Regions; BAU, business as usual scenario; PBC, perennial biomass crops.

decreases to 15% of overall grassland. The production of grassland silage for biogas decreases by around 12% and 8% for feed production in BAU and BIO_mid at Baden-Wuerttemberg level through expanded cultivation of PBC. The reduction of feed production in both BIO_hi scenarios decreases by 10%.

In all regions, the cultivation option of PBC on grassland leads to a significant reduction in forage production. The results are particularly interesting in regions with intensive dairy farming (AER 5), intensive livestock production (AER 6), and the mixed farming region (AER 8). These regions are characterized by a high competition for grassland by cattle

farming and they have (almost) no unused grassland even without cultivation of PBC on grassland. If, however, PBC cultivation is allowed on grassland, those regions cultivate PBC on a significant area of grassland (29%–45%). Despite this increase in competition for grassland, livestock farming is not reduced. The farms in these regions increase the intensity of grassland production and purchase more feed to compensate for grassland area now used for PBC. Other regions (like AER 3 and AER 7) still have, despite the cultivation of PBC on grassland, a comparatively high share of unused grassland (>10%). These regions have a relatively high endowment of marginal grassland, where the cultivation of biogas feedstock or PBC does not cover costs or is not possible due to production conditions, respectively. The gross margin increases by 6% in BAU and BIO_mid and by 7% through the PBC cultivation on grassland. AER 5 could benefit the most from the PBC cultivation on grassland and increase the gross margin by almost 30%, due to the intensification of grassland use.

3.5.2 | Effects of a reduced PBC price

The sensitivity analysis (Figure 8) shows that lower PBC prices first affect SRC cultivation. Miscanthus has a higher gross margin than SRC and is therefore less sensitive to price declines. With a price reduction of 40%, the area of miscanthus decreases as well. With a 20% reduction in PBC price, the production of PBC reduces by 25% in BAU and slightly in BIO_hi. At 60% lower prices, the cultivation of PBC completely vanishes in all scenarios. The major part of the substitution of the PBC area is done by cereal production (around 73%) and additionally by oilseed production (9%), which both vary only little between the scenarios. The remaining area is used to expand the cultivation area of corn and silage maize.
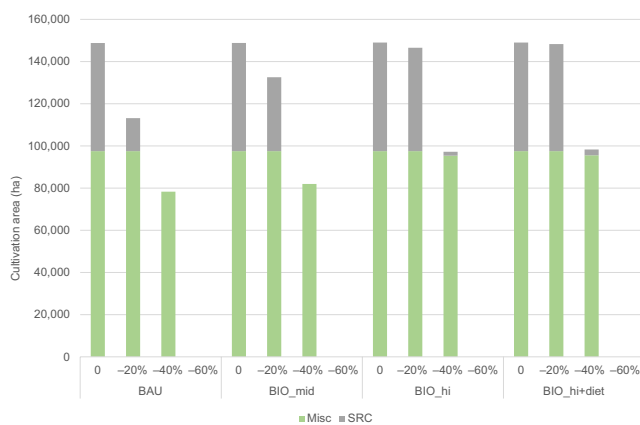
FIGURE 8 Effects of a reduced price of perennial biomass crops on miscanthus (Misc) and short rotation coppice (SRC) cultivation in Baden-Wuerttemberg per bioeconomy scenario in 2050

3.5.3 | Effects of climate change-based yield changes

In the following, we present the effects of climate change on yields for the fertile cropping region AER 1 and the low mountain region AER 6. In order to show the maximum effect, we compare the climate change sensitivity for the BAU and BIO_hi scenario.

In general, the considered climate change scenarios have a negative impact on the gross margin in both regions, whereas the decline increases over time. However, it has no effect on the PBC cultivation area, because its comparative advantage remains. In the BAU scenario, AER 6, the loss in gross margin is lower (−4%) than in AER 1 with −6% in 2050. The stronger decline in cereal and rapeseed yields in AER 6 is overcompensated for by the slight increase in maize yields. Despite the different comparative effects, the gross margin decreases at the same level in the BIO_hi scenario in both regions, because silage maize production as a biogas feedstock is not possible in that scenario.

The considered climate change scenarios have different effects on the two examined regions (AER 1 and AER 6). In AER 1, the biggest effect of the considered climate change can be observed on the cultivation of silage maize. This effect has to be distinguished between biogas feedstock and feed. The declining yield of silage maize as biogas feedstock reduces the comparative advantage, which results in a smaller cultivation area. The cultivation of silage maize for feed, however, increases because livestock farming has a comparative advantage to other crop production. As a result, more maize cultivation is required in order to produce the necessary feed. Wheat has a robust comparative advantage in this region due to the high-yield level, and therefore, the considered yield decline is not big enough to nullify it.

In AER 6, the considered climate change effects slightly increase the yields of corn and silage maize production, while the yield of wheat significantly decreases. This results in the 18% increase in the maize cultivation area in the BAU scenario. The abolished use of silage maize as a biogas substrate in the BIO_hi scenario and the different price ratio results in no change in crop rotation between the climate change scenario and the reference.

4 | DISCUSSION

4.1 | General impacts of modeled scenarios

The results of this study highlight that the transition of a fossil-based economy to a bio-based economy can cause different impacts on agricultural production in different regions, and can even contradict within subregions and/or between farm typologies. This characteristic coincides with results of other studies that use a model linkage at different aggregation

levels (Offermann et al., 2015). The model results of EFEM show a general increase in the gross margin of farms in Baden-Württemberg over time and due to the expansion of the bioeconomy sector. However, there are winners and losers of this development. The results indicate that the marginal agricultural regions will not benefit from an expanding bioeconomy, which will thus further increase the economic disadvantage compared to highly productive locations and furthermore increase the structural change in those regions. If this is not politically or socially desired, agricultural subsidies have to be adopted accordingly.

We compared our results with findings by Offermann et al. (2018) in order to validate our simulations. The comparison shows only a small deviation between baseline and BAU scenarios of both studies. However, the effects of the abolishment of market protection for beef and sugar beet differ between the studies. The less favorable production conditions of beef and sugar beet in Baden-Wuerttemberg lead to a stronger reduction in production in our modeling with EFEM. In agreement with Banse et al. (2016), the modeled production shift shows similar impacts on the structures of the agricultural production in specific bioeconomy scenarios. The results of their impact assessment of a bioeconomy implementation show a rising cultivation area of cereals, while the cultivation area of the other arable crops decreases by 2025, which is in accordance with our results of the bioeconomy scenarios in 2030.

The modeled impacts are driven by several factors, however, which are not all caused by the direct development of the bioeconomy. The reduced availability of arable land leads to an overall decline in biomass production and consequently intensifies the competition among agricultural activities. This effect is particularly crucial in both Baden-Wuerttemberg and Germany in general, as there is no significant fallow land that could be used to increase the available cultivation area.

4.2 | PBC adoption

The assumed framework conditions of the bioeconomy sector in the different scenarios lead to a general expansion of PBC on arable land by substituting other agricultural crops. The sensitivity analysis of the PBC prices shows a high elasticity of the cultivation area in Baden-Wuerttemberg, as the cultivation declines by 25% based on a 20% decrease. This shows the importance of determining the base price. However, the assumed base price of PBC that is derived from heat values also seems appropriate, as the use of biomass for materials has to compete with its energy use, especially with the desired goal of reducing use of fossil resources. This also shows the need to improve existing new lignocellulosic value chains and to develop new ones (Dahmen, Lewandowski, Zibek, & Weidtmann, 2019). Furthermore, our results are mainly driven by farm profitability from price developments in

bioeconomy scenarios. However, the expansion of PBC can also trigger a resistance in society, similar to the resistance against the regionally widespread cultivation of silage maize as biogas feedstock in Germany. Therefore, the acceptance of the local as well as regional population should be examined before wide political promotion.

4.3 | Impacts of climate change and technological progress

Technological progress counterparts the declining cultivation area. Nevertheless, it is uncertain that this development will continue like this, especially in view of climate change. Regarding the latter, the assessed effects in model calculations of climate change indicate, in particular, a change in the comparative advantages of crops within and between regions. This is likely to affect the optimal crop rotation and therefore change the agricultural production. The general development, however, results in a decline of farms' gross margins. Wolf et al. (2015) argue that the combination of change with technologies and management adaptions lead to no significant effect on farms' profitability in central Europe. Such adoption strategies are not integrated in EFEM so far, but should be considered in any future modeling that assesses climate change-related scenario.

4.4 | Use of grassland

Grassland results show a high unused technical potential of biomass in Baden-Wuerttemberg, which could be used within bioeconomic value-added chains. The cultivation of PBC on grassland, however, shows significant regional differences. On the one hand, regions with a high share of unused grassland cultivate PBC without changing the production. For these regions, the implementation of PBC with a special focus on marginal land could be useful (Wagner et al., 2019). On the other hand, regions with an already intensive grassland utilization further increase this intensity of utilization. The maximum cultivation area of PBC is in accordance with the identified suitable land availability for PBC of Aust et al. (2014). Beside PBC cultivation, the unused grassland could also be a potential biomass feedstock for biorefineries and, in this way, used for new value chains in the bioeconomy (Mandl, 2010). However, biomass resources with a high water content in the harvested product have relatively high transport costs, which therefore must be given a particular consideration (Zhang et al., 2018). In accordance with other studies, the decreasing use of grassland in marginal regions seems likely due to the decreased competiveness of cattle farming in those regions (Ketzer, Rösch, & Haase, 2017). If no new profitable value chains for grassland as feedstock will be developed, nonuse will result in a succession that converts grassland to forest. This forest could also be used as lignocellulosic feedstock

in the bioeconomy in the long term, but this conversion seems largely undesirable, because grassland, especially extensively used grassland, has a comparatively high ecological performance (Öckinger, Eriksson, & Smith, 2006). In general, appropriate subsidies and a certain policy framework must be provided, if the intensive grassland should be preserved from intensification through expanded biomass production and extensive grassland from succession based on nonuse.

4.5 | Silage maize as biogas feedstock

Biogas production is an important consumer of agricultural biomass in Baden-Wuerttemberg, but the demand greatly depends on political subsidies, due to comparatively high feedstock costs. However, the political environment regarding agricultural biogas production seems largely unpromising and the sector is already shifting toward flexible demand-driven production. Additionally, high value production seems the appropriate developing path of biogas use (Bahrs & Angenendt, 2019). Both will result in a smaller demand for agricultural biogas feedstock and the redundant area could be used for other food and feed. The effect on the profitability of the farms will depend on whether they are able to compensate for the reduced demand with a higher product price for the particular products.

4.6 | Change in diet

Another core parameter in the transition from a fossil-based economy to a bio-based economy is the declining consumption of resources in industrialized countries (Hedenus, Wirsenius, & Johansson, 2014). A change in diet of the population in western countries is one part of this reduction. However, at Baden-Wuerttemberg level, the effect of the resulting price development of livestock and plant products has far less of an effect on livestock production than the price development over time in the baseline. However, the change in diet will reduce the import of livestock products, because Baden-Wuerttemberg has a relatively low level of self-sufficiency of around 55% for livestock products (except poultry <20%) in 2016 (LEL, 2017a). Nevertheless, the profitability of the intensive livestock farms is significantly diminishing due to the price development of the change in diet.

4.7 | General limitations of the model approach

Economic models are always based on a simplified representation of reality. Additionally, the complexity of the development of the bioeconomy is high. For this reason, the results of this study also show some limitations.

Although the important crops are integrated, crop residues as feedstock are not considered, because they are not implemented

in the model linkage of ESIM and TIMES-PanEU. However, this biomass has some potential in Baden-Wuerttemberg (Petig, Rudi, Angenendt, Schultmann, & Bahrs, 2019). New crops, such as PBC, are lacking regionally differentiated yield data. The implementation, therefore, depends on expert opinion rather the yield statistics that are often based on a few field trials. More detailed production data of PBC could help to improve the spatially differentiated implementation in EFEM. The assumed technical progress of considered crops is a suitable assumption as presented in the method section, but might also reach a biological yield limit. This justifies a separate analysis in the context of bioeconomy in the future, but has so far been omitted in order to maintain consistency with ESIM.

Another limitation consists of the missing logistic assessment of the production of PBC and biogas substrates. Logistics has a strong impact on profitability of production, especially for regions with poor transport links, because transportation costs in biomass value chains account for a large share of total biomass costs (Ba, Prins, & Prodhon, 2016). However, the number of potential plants (e.g., biorefinery) is quite low compared to the number of farms, which would selectively affect the farms results of EFEM. This would strongly distort the extrapolation to regional results and is therefore not directly implemented in EFEM. For biogas, however, survey data allow for a spatial differentiation, but for PBC, there are no such data.

Structural changes in the agricultural sector may be accelerated or slowed by future policy changes, especially to the Common Agricultural Policy (CAP) of the EU. Although linear regression of structural changes is a suitable assumption as presented in the method section, future changes in policy framework may result in major changes.

4.8 | Summary and future research implications

This study assessed the impacts of future bioeconomy scenarios at farm level in the German federal state of Baden-Wuerttemberg by downscaling agricultural market data at EU and country level. In this approach, the results of the agricultural sector model ESIM and the energy sector model TIMES-PanEU were downscaled to the farm model EFEM. PBC cultivation shows a high competiveness in all regions and the general development shows an increasing profitability in agricultural production in Baden-Wuerttemberg. However, results show contrasting effects at regional level and for the different production foci of farms. Regions with pronounced cattle farming activities and marginal regions will not profit from the overall growth of the bioeconomy. By contrast, fertile regions with a focus on arable farming not only profit from the expansion of PBC but also from the market development of other cash crops. This effect can also be seen at farm level. The arable farm profits from

development and dairy farms suffer economic losses. This is accompanied by increased competition in already intensive regions on the one hand, and on the other hand, marginal locations and extensive production systems suffer economic losses.

For future research, an assessment of the general development of bioeconomy scenarios with decentralized biorefineries may be interesting, because it could depict a regionally localized demand for the specific agricultural biomass of biorefineries. Feedstock provision and the transportation cost of such biorefineries will probably have additional effects on regional biomass prices and therefore affect regional production. Furthermore, a holistic assessment of ecological impacts due to the change in production pattern should be performed. This includes effects not only on soil, water, and biodiversity but also on GHG emissions, especially when conversion from grassland to arable is allowed. A combined cultivation system of food crops and PBC could help to reduce negative ecological effects like fertilizer runoff or biodiversity loss due to an intensification of agricultural production (Acharya & Blanco-Canqui, 2018; Ferrarini et al., 2017; Jørgensen, 2011). Finally, an assessment of policy support measures with a specific focus on less competitive marginal regions and extensive production systems may bring some interesting insights in order to determine the economic effort to preserve ecologically beneficial production systems.

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REFERENCES

Acharya, B. S., & Blanco-Canqui, H. (2018). Lignocellulosic-based bioenergy and water quality parameters: A review. *GCB Bioenergy*, *10*(8), 504–533. https://doi.org/10.1111/gcbb.12508

Alexandratos, N., & Bruinsma, J. (2012). World Agriculture towards 2030/2050: The 2012 revision. ESA working paper No. 12–03. Retrieved from http://www.fao.org/docrep/016/ap106e/ap106e.pdf

Angulo, C., Rötter, R., Lock, R., Enders, A., Fronzek, S., & Ewert, F. (2013). Implication of crop model calibration strategies for assessing regional impacts of climate change in Europe. *Agricultural and Forest Meteorology*, *170*, 32–46. https://doi.org/10.1016/j.agrformet.2012.11.017

Aust, C., Schweier, J., Brodbeck, F., Sauter, U. H., Becker, G., & Schnitzler, J.-P. (2014). Land availability and potential biomass production with poplar and willow short rotation coppices in Germany. *GCB Bioenergy*, *6*(5), 521–533. https://doi.org/10.1111/gcbb.12083

Ba, B. H., Prins, C., & Prodhon, C. (2016). Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective. *Renewable Energy*, *87*, 977–989. https://doi.org/10.1016/j.renene.2015.07.045

Bahrs, E., & Angenendt, E. (2019). Status quo and perspectives of biogas production for energy and material utilization. *GCB Bioenergy*, *11*(1), 9–20. https://doi.org/10.1111/gcbb.12548

Banse, M., Janzen, N., Junker, F., Kreins, P., Offermann, F., Salamon, P., & Weimar, H. (2016). Modelling the bioeconomy: Linkages between agricultural, wood and energy markets. Braunschweig. Retrieved from Johann Heinrich von Thünen-Institut website http://literatur.thuenen.de/digbib_extern/dn056932.pdf

Bayrische Landesanstalt für Landwirtschaft (LfL). (2018). LfL-Deckungsbeiträge und Kalkulationsdaten – Chinaschilf (Miscanthus) [Contribution margin and calculation data – Miscanthus]. Retrieved from https://www.stmelf.bayern.de/idb/miscanthus.html

Bell, J., Paula, L., Dodd, T., Németh, S., Nanou, C., Mega, V., & Campos, P. (2018). EU ambition to build the world's leading bioeconomy—Uncertain times demand innovative and sustainable solutions. *New Biotechnology*, *40*(Pt A), 25–30. https://doi.org/10.1016/j.nbt.2017.06.010

Blesl, M., Kober, T., Kuder, R., & Bruchof, D. (2012). Implications of different climate protection regimes for the EU-27 and its member states through 2050. *Climate Policy*, *12*(3), 301–319. https://doi.org/10.1080/14693062.2011.637815

Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMEL). (2016). *Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland: Jahrbuch 2016 (60. Jahrgang)*. Münster-Hiltrup, Germany: Landwirtschaftsverlag GmbH. Retrieved from https://www.statistik-bw.de/Landwirtschaft/Agrarstruktur/Betriebe-LFGK.jsp

Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V. (C.A.R.M.E.N.). (2018). Preisentwicklung bei Waldhackschnitzeln – Jahresmittelwerte (Price development of forrest wood chips – Annual averages). Retrieved from https://www.carmen-ev.de/infothek/preisindizes/hackschnitzel/jahresmittelwerte/226-preisentwicklung-bei-waldhackschnitzeln-jahresmittelwerte

Choi, H. S., Grethe, H., Entenmann, S. K., Wiesmeth, M., Blesl, M., & Wagner, M. (2019). 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. *GCB Bioenergy*, *11*(3), 483–504. https://doi.org/10.1111/gcbb.12596

Commission Directorate-General for Agriculture and Rural Development (DG AGRI). (2017). Agricultural markets and prices. Retrieved from https://ec.europa.eu/agriculture/markets-and-prices_en

Cordts, A. (2015). *Nachhaltiger Lebensmittelkonsum: Eine empirische Analyse am Beispiel von Bio-Produkten und Fleisch* (1st ed.). Göttingen, Germany: Cuvillier Verlag. Retrieved from https://ebookcentral.proquest.com/lib/gbv/detail.action?docID=5023681

Dahmen, N., Lewandowski, I., Zibek, S., & Weidtmann, A. (2019). Integrated lignocellulosic value chains in a growing bioeconomy: Status quo and perspectives. *GCB Bioenergy*, *11*(1), 107–117. https://doi.org/10.1111/gcbb.12586

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., … Toppinen, A. (2017). Green, circular, bio economy: A comparative analysis of sustainability avenues. *Journal of Cleaner Production*, *168*, 716–734. https://doi.org/10.1016/j.jclepro.2017.09.053

Deppermann, A., Blesl, M., Boysen, O., Grethe, H., & Bruchof, D. (2016). Linkages between the energy and agricultural sectors: Insights from European Union greenhouse gas mitigation scenarios. *Mitigation and Adaptation Strategies for Global Change*, *21*(5), 743–759. https://doi.org/10.1007/s11027-014-9621-0

EEG. (2017). Gesetz für den Ausbau erneuerbarer Energien – EEG 2017 (German Renewable Energy Act). Berlin, Germany: Deutscher Bundestag.

European Commission (EC). (2013). EU energy, transport and GHG emission trends to 2050 - Reference scenario 2013. Retrieved from https://ec.europa.eu/transport/sites/transport/files/media/publications/doc/trends-to-2050-update-2013.pdf

European Commission (EC). (2016). Regulation (EC) no 1059/2003 of the European Parliament and of the Council of 26 May 2003 on the establishment of a common classification of territorial units for statistics (NUTS): NUTS – Nomenclature of territorial units for statistics. Retrieved from http://ec.europa.eu/eurostat/web/nuts/background

European Commission (EC). (2018). Farm accountancy data network (FADN). Retrieved from http://ec.europa.eu/agriculture/rica/index.cfm

Fachagentur Nachwachsende Rohstoffe e.V. (FNR). (2018). Erhebung, Aufbereitung und Analyse statistischer Daten zum Anbau und zur Verarbeitung nachwachsender Rohstoffe und Energiepflanzen in Deutschland sowie Weiterentwicklung von Methoden hierzu (NRstat). Retrieved from https://www.fnr.de/index.php?xml:id=11150&fkz=22004416

Ferrarini, A., Fornasier, F., Serra, P., Ferrari, F., Trevisan, M., & Amaducci, S. (2017). Impacts of willow and miscanthus bioenergy buffers on biogeochemical N removal processes along the soil-groundwater continuum. *GCB Bioenergy*, *9*(1), 246–261. https://doi.org/10.1111/gcbb.12340

Gillich, C., Narjes, M., Krimly, T., & Lippert, C. (2019). Combining choice modeling estimates and stochastic simulations to assess the potential of new crops-The case of lignocellulosic perennials in Southwestern Germany. *GCB Bioenergy*, *11*(1), 289–303. https://doi.org/10.1111/gcbb.12550

Grethe, H., Atavia, M., Banse, M., Boysen, O., Deppermann, A., & Nolte, S. (2012). European Simulation Model (ESIM): Documentation (model code, parameterization, database). Retrieved from http://www.uni-hohenheim.de/qisserver/rds?state=medialoader&objectxml:id=7530&application=lsf

Güsewell, J., Härdtlein, M., & Eltrop, L. (2019). A plant-specific model approach to assess effects of repowering measures on existing biogas plants: The case of Baden-Wuerttemberg. *GCB Bioenergy*, *11*(1), 85–106. https://doi.org/10.1111/gcbb.12574

Hazell, P., & Wood, S. (2008). Drivers of change in global agriculture. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *363*(1491), 495–515. https://doi.org/10.1098/rstb.2007.2166

Hedenus, F., Wirsenius, S., & Johansson, D. J. A. (2014). The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Climatic Change*, *124*(1–2), 79–91. https://doi.org/10.1007/s10584-014-1104-5

Hübener, H., Bülow, K., Fooken, C., Früh, B., Hoffmann, P., Höpp, S., … Woldt, M. (2017). ReKliEs-De Ergebnisbericht, Tech. rep., Hessian Agency for Nature, Environment and Geology (HLNUG).

Imbert, E., Ladu, L., Morone, P., & Quitzow, R. (2017). Comparing policy strategies for a transition to a bioeconomy in Europe: The case of Italy and Germany. *Energy Research & Social Science*, *33*, 70–81. https://doi.org/10.1016/j.erss.2017.08.006

Institut für Energiewirtschaft und Rationelle Energieanwendung (IER). (2013). Biogasanlagen in Baden-Württemberg Stand der Technik, wirtschaftliche Aspekte, Klimarelevanz und Optimierungspotenziale: Ergebnisse aus einer Umfrage für das Betriebsjahr 2012. Retrieved from Universität Stuttgart website http://www.ier.uni-stuttgart.de/linksdaten/biogas/BG-Betreiber-Umfrage-2012_Okt-13.pdf

Janssen, S., Louhichi, K., Kanellopoulos, A., Zander, P., Flichman, G., Hengsdijk, H., … van Ittersum, M. K. (2010). A generic bio-economic farm model for environmental and economic assessment of agricultural systems. *Environmental Management*, *46*(6), 862–877. https://doi.org/10.1007/s00267-010-9588-x

Jørgensen, U. (2011). Benefits versus risks of growing biofuel crops: The case of Miscanthus. *Current Opinion in Environmental Sustainability*, *3*(1–2), 24–30. https://doi.org/10.1016/j.cosust.2010.12.003

Kanellopoulos, A., Reidsma, P., Wolf, J., & van Ittersum, M. K. (2014). Assessing climate change and associated socio-economic scenarios for arable farming in the Netherlands: An application of benchmarking and bio-economic farm modelling. *European Journal of Agronomy*, *52*, 69–80. https://doi.org/10.1016/j.eja.2013.10.003

Kaule, G., Stahr, K., Zeddies, J., Angenendt, E., Bakara, H., Billen, N., & Schwarz-v. Raumer, H.-G. (2011). Forschungsbericht BWPLUS: Nachwachsende Energieträger und Biodiversität: naturschutzbezogene und ökonomische Entwicklung und Bewertung von Anbauszenarien (NawEnNat) und Abschätzung der Produktionspotenziale für den Anbau von Energiepflanzen zur CO2-Bindung in Baden-Württemberg und deren ökologische und ökonomische Bewertung. Retrieved from http://www.fachdokumente.lubw.baden-wuerttemberg.de/servlet/is/100869/

Kazenwadel, G. (1999). *Ökonomisch/ökologische Beurteilung von regionalen Agrar- und Umweltprogrammen in der Europäischen Union*. Agrarwirtschaft Sonderheft. 162. Bergen/Dumme: Agrimedia.

Ketzer, D., Rösch, C., & Haase, M. (2017). Assessment of sustainable Grassland biomass potentials for energy supply in Northwest Europe. *Biomass and Bioenergy*, *100*, 39–51. https://doi.org/10.1016/j.biombioe.2017.03.009.

Knox, J., Daccache, A., Hess, T., & Haro, D. (2016). Meta-analysis of climate impacts and uncertainty on crop yields in Europe. *Environmental Research Letters*, *11*(11), 113004. https://doi.org/10.1088/1748-9326/11/11/113004

Krimly, T., Angenendt, E., Bahrs, E., & Dabbert, S. (2016). Global warming potential and abatement costs of different peatland management options: A case study for the Pre-alpine Hill and Moorland in Germany. *Agricultural Systems*, *145*, 1–12. https://doi.org/10.1016/j.agsy.2016.02.009

Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL). (2017). MaKost – Maschinen- und Reparaturkosten (Machinery and repair costs). Retrieved from http://daten.ktbl.de/makost/

Landesanstalt für Entwicklung der Landwirtschaft und der ländlichen Räume (LEL). (2017a). Agrarmärkte – Jahresheft 2017 (32. Jahrgang). Retrieved from http://lel-bw.de/pb/,Lde/5244027

Landesanstalt für Entwicklung der Landwirtschaft und der ländlichen Räume (LEL). (2017b). Kalkulationsdaten Marktfrüchte. Retrieved

from http://www.lel-bw.de/pb/Lde/Startseite/Unsere+Themen/Kalkulationsdaten+Marktfruechte

Landesanstalt für Entwicklung der Landwirtschaft und der ländlichen Räume (LEL). (2017c). Kalkulationsdaten Tierhaltung. Retrieved from http://www.lel-bw.de/pb/Lde/Startseite/Unsere+Themen/Tierhaltung

Landesanstalt für Entwicklung der Landwirtschaft und der ländlichen Räume (LEL). (2018). Landwirtschaftliche Betriebsverhältnisse und Buchführungsergebnisse Baden-Württemberg: Wirtschaftsjahr 2016/2017 (No. 66). Retrieved from https://www.landwirtschaft-bw.info/pb/MLR.LEL-SGLde_DE/Startseite/Unsere+Themen/Landwirtschaftliche+Betriebsverhaeltnisse+Baden_Wuerttemberg

Lehtonen, O., & Okkonen, L. (2013). Regional socio-economic impacts of decentralised bioeconomy: A case of Suutela wooden village, Finland. *Environment, Development and Sustainability*, *15*(1), 245–256. https://doi.org/10.1007/s10668-012-9372-6

Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., … van Ittersum, M. (2010). FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. *Agricultural Systems*, *103*(8), 585–597. https://doi.org/10.1016/j.agsy.2010.06.006

Mandl, M. G. (2010). Status of green biorefining in Europe. *Biofuels, Bioproducts and Biorefining*, *4*(3), 268–274. https://doi.org/10.1002/bbb.219.

Mantau, U. (2012). *Holzrohstoffbilanz Deutschland: Entwicklungen und Szenarien des Holzaufkommens und der Holzverwendung von 1987 bis 2015*. Hamburg: Johann Heinrich von Thünen-Institut (vTI), Bundesforschungsinstitut für Ländliche Räume, Wald und Fischerei.

Mantau, U. (2015). Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. *Biomass and Bioenergy*, *79*, 28–38. https://doi.org/10.1016/j.biombioe.2014.08.013

Mantau, U., Saal, U., Prins, K., Steierer, F., Lindner, M., Verkerk, H., … Anttila, P. (2010). *Real potential for changes in growth and use of EU forests*. Hamburg: EUwood, Final report. http://www.federlegnoarredo.it/ContentsFiles%5C0000136150_EUwood_final_report_2010.pdf

McGlade, C., & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature*, *517*(7533), 187–190. https://doi.org/10.1038/nature14016

Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg (MLR). (2016). Grünlandumwandlungsverbot – Wertvoller Beitrag zum Klima- und Artenschutz. Retrieved from https://mlr.baden-wuerttemberg.de/de/unsere-themen/landwirtschaft/umweltvertraeglicher-pflanzenbau/gruenlandumwandlungsverbot/

Mubareka, S., Jonsson, R., Rinaldi, F., Fiorese, G., San-Miguel-Ayanz, J., Sallnäs, O., … Kitous, A. (2014). An integrated modelling framework for the forest-based bioeconomy. *bioRxiv* (preprint). https://doi.org/10.1101/011932

Öckinger, E., Eriksson, A. K., & Smith, H. G. (2006). Effects of grassland abandonment, restoration and management on butterflies and vascular plants. *Biological Conservation*, *133*(3), 291–300. https://doi.org/10.1016/j.biocon.2006.06.009

Offermann, F., Banse, M., Deblitz, C., Gocht, A., González-Mellado, A., Kreins, P., … Sanders, J. (2015). Thünen baseline 2015–2025: Agri-economic projections for Germany. *Landbauforschung (Applied Agricultural and Forestry Research)*, *66*(4), 240–257. https://doi.org/10.3220/LBF1481641394000

Offermann, F., Banse, M., Freund, F., Haß, M., Kreins, P., Laquai, V., … Salamon, P. (2018). *Thünen-Baseline 2017–2027: Agrarökonomische Projektionen für Deutschland* (Vol. 56). Thünen Report. Braunschweig, Germany: Thünen-Institut, Bundesforschungsinstitut für Ländliche Räume, Wald und Fischerei.

Olsson, L., & Saddler, J. (2013). Biorefineries, using lignocellulosic feedstocks, will have a key role in the future bioeconomy. *Biofuels, Bioproducts and Biorefining*, *7*(5), 475–477. https://doi.org/10.1002/bbb.1443

Petig, E., Rudi, A., Angenendt, E., Schultmann, F., & Bahrs, E. (2019). Linking a farm model and a location optimization model for evaluating energetic and material straw valorization pathways-A case study in Baden-Wuerttemberg. *GCB Bioenergy*, *11*(1), 304–325. https://doi.org/10.1111/gcbb.12580

Piotrowski, S., Essel, R., Carus, M., Dammer, L., & Engel, L. (2015). Nachhaltig nutzbare Potenziale für Biokraftstoffe in Nutzungskonkurrenz zur Lebens-und Futtermittelproduktion. Bioenergie sowie zur stofflichen Nutzung in Deutschland, Europa und der Welt Retrieved from http://bio-based.eu/ecology/#biomassepotenziale

Schäfer, M. (2006). Abschätzung der Emissionen klimarelevanter Gase aus der Landwirtschaft Baden-Württembergs und Bewertung von Minderungsstrategien unter Nutzung eines ökonomisch-ökologischen Regionalmodells. Zugl.: Hohenheim University Dissertation. Berichte aus der Agrarwissenschaft. Aachen: Shaker.

Schwarz-v. Raumer, H.-G., Angenendt, E., Billen, N., & Jooß, R. (2017). Economic and ecological impacts of bioenergy crop production—A modeling approach applied in Southwestern Germany. *AIMS Agriculture and Food*, *2*(1), 75–100. https://doi.org/10.3934/agrfood.2017.1.75

Statistisches Bundesamt (DESTATIS). (2017). Fachserie 3, Reihe 3 Landwirtschaftliche Bodennutzung und pflanzliche Erzeugung. Retrieved from www.destatis.de

Thünen-Institut. (2017). Dritte Bundeswaldinventur – Ergebnisdatenbank. Retrieved from https://bwi.info

Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., de Ruiter, P. C., van der Putten, W. H., Birkhofer, K., … Hedlund, K. (2015). Intensive agriculture reduces soil biodiversity across Europe. *Global Change Biology*, *21*(2), 973–985. https://doi.org/10.1111/gcb.12752

United Nations (UN). (2017). World population prospects: The 2017 revision. Retrieved from https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html

U.S. Energy Information Administration (EIA). (2013). International Energy Outlook 2013. Retrieved from https://www.eia.gov/outlooks/ieo/pdf/0484(2013).pdf

van Meijl, H., Tsiropoulos, I., Bartelings, H., Hoefnagels, R., Smeets, E., Tabeau, A., & Faaij, A. (2018). On the macro-economic impact of bioenergy and biochemicals – Introducing advanced bioeconomy sectors into an economic modelling framework with a case study for the Netherlands. *Biomass and Bioenergy*, *108*, 381–397. https://doi.org/10.1016/j.biombioe.2017.10.040.

van Ittersum, M. K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., … Wolf, J. (2008). Integrated assessment of agricultural systems – A component-based framework for the European Union (SEAMLESS). *Agricultural Systems*, *96*(1–3), 150–165. https://doi.org/10.1016/j.agsy.2007.07.009

Wagner, M., Mangold, A., Lask, J., Petig, E., Kiesel, A., & Lewandowski, I. (2019). Economic and environmental performance of miscanthus cultivated on marginal land for biogas production. *GCB Bioenergy*, *11*(1), 34–49. https://doi.org/10.1111/gcbb.12567

Wicke, B., van der Hilst, F., Daioglou, V., Banse, M., Beringer, T., Gerssen-Gondelach, S., … Faaij, A. P. C. (2015). Model collaboration for the improved assessment of biomass supply, demand, and impacts. *GCB Bioenergy*, *7*(3), 422–437. https://doi.org/10.1111/gcbb.12176

Wolf, J., Kanellopoulos, A., Kros, J., Webber, H., Zhao, G., Britz, W., … de Vries, W. (2015). Combined analysis of climate, technological and price changes on future arable farming systems in

Europe. *Agricultural Systems*, *140*, 56–73. https://doi.org/10.1016/j.agsy.2015.08.010

Zhang, H., Lopez, P. C., Holland, C., Lunde, A., Ambye-Jensen, M., Felby, C., & Thomsen, S. T. (2018). The multi-feedstock biorefinery – Assessing the compatibility of alternative feedstocks in a 2G wheat straw biorefinery process. *GCB Bioenergy*, *10*(12), 946–959. https://doi.org/10.1111/gcbb.12557

Zimmermann, A., Heckelei, T., & Domínguez, I. P. (2009). Modelling farm structural change for integrated ex-ante assessment: Review of methods and determinants. *Environmental Science & Policy*, *12*(5), 601–618. https://doi.org/10.1016/j.envsci.2009.01.014

Zimmermann, A., Webber, H., Zhao, G., Ewert, F., Kros, J., Wolf, J., … de Vries, W. (2017). Climate change impacts on crop yields, land use and environment in response to crop sowing dates and thermal time requirements. *Agricultural Systems*, *157*, 81–92. https://doi.org/10.1016/j.agsy.2017.07.007

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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