The National and Regional Impact of the EU Bioeconomy Strategies on the Agri-Food Sector: Insights from Germany

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Abstract

The bioeconomy strategy of the European Union aims to balance three distinct goals: food security, the sustainable use of renewable resources for industrial purposes, and environmental protection. This study uses an integrated computable general equilibrium model to simulate the impacts of selected elements of the EU bioeconomy strategy on German agriculture at national and regional level up to 2050. An improved productivity of the crop sector substantially increases production and export/import ratio of crop outputs and reduces crop prices, while only moderately expanding cropland. The improved crop productivity would help to reduce the competition for resources between non-food and food biomass use as well as between crop and livestock production. An increasing conversion efficiency of agricultural biomass for use in biorefineries alone is unlikely to have a significant impact on the German bioeconomy. Overall, the results suggest the need for further efforts to improve crop productivity and effective complementary measures supporting the development of transformative technologies and changes in consumer preferences to ensure a minimum level of biomass use in the chemical sector.

Keywords

bioeconomy; biomass productivity; conversion efficiency; agriculture; land use change

1 Introduction

In the context of the general quest for more sustainable production processes and resource use, many countries across the globe adopted so-called bioeconomy strategies. The European Union (EU) established its first Bioeconomy Strategy in 2012 (EUROPEAN COMMISSION, 2012) and updated it in 2018 (EUROPEAN COMMISSION, 2018) aiming to balance three distinct goals: food security, the sustainable use of renewable resources for industrial purposes, and environmental protection.[1]

A transition to a bioeconomy may offer both opportunities and risks for sustainable development, and thus a positive impact of bioeconomy strategies on sustainable development is not guaranteed.[2] The objective of this study is to identify the impacts of selected bioeconomy strategies: a) improved productivity of the cropping sectors as one of the main providers of biomass and b) improved efficiency of the use of biomass in the biorefinery sector in Germany. We evaluate the impacts on the production of crops and associated land use at national and regional levels. In addition, we look at the impacts on activities competing for biomass resources such as biomass-based products as well as processed food, and sectors such as livestock production that compete with the crop sector for the available land.

We simulate the impact of the EU bioeconomy along three different pathways. First, we evaluate the outcome of a scenario where no additional effort is made to transform to a bioeconomy (the baseline scenario). Then, we consider the transitions along two pathways: increased productivity of cropping activities as a primary source of biomass production by 0.5% annually above its historical growth trend ("biomass expansion" scenario) and increased conversion efficiency of the use of biomass in biochemical industry by 1.5% annually above its historical growth trend ("biomaterial expansion" scenario). The baseline reflects the Shared Socio-Economic Pathway (SSP) 2 and thus represents a business-as-usual scenario.[3] This scenario mostly extrapolates historical global trends, where the transition to a bioeconomy is not actually taking off due to a lack of effective political and so-

[1] The EU bioeconomy strategy strives to maximize the contribution of the EU to the 2030 Agenda for Sustainable Development of the United Nations (UN) and its 17 Sustainable Development Goals (SDGs), to the Paris Climate Agreement, as well as to the EU's sustainable and circular bioeconomy strategy.

[2] For example, a transition to bioeconomy might increase pressure on the land use in biomass production or threaten the expansion of activities, such as food production, which compete for agricultural intermediate inputs vis-a-vis biomaterial producing activities.

[3] See Online Appendix A for the qualitative description of SSP2.

DOI: 10.30430/gjae.2023.0274

cietal strategies (STURM and BANES, 2021). The "biomass expansion" scenario reflects the ongoing and expected transformation of breeding and farm management through innovative technologies such as digital farming, agricultural robots and phenotyping technologies (SHANG et al., 2021). The "biomaterial expansion" scenario reflects the EU's chemical industry's expansion of biochemicals output by developing more efficient and cost-effective processing of biological feedstock into a range of bio-based products (DEJONG et al., 2020). We perform the simulation using a regionally differentiated dynamic Computable General Equilibrium (CGE) model with linkages to the global and local drivers of economic changes.

This study contributes to the literature in two ways. First, we simulate impacts at a high regional resolution (NUTS-2)[4], which is important as regions are heterogeneous in their economic structure and endowments. Second, we contribute technically to the literature by introducing a framework that enables such simulations at regional level while still incorporating the global and regional drivers of economic changes. Most studies of the impact of transition policies implicitly assume that economic structure over time remains the same. Investigating the long-term impact, however, requires allowing for changes in national economic structure (BRITZ and ROSON, 2018) and the divergence of the regional economies from the national level based on regional characteristics (BRITZ et al., 2019).

The remainder of the paper is organized as follows. A background and related literature section provides definitions of bioeconomy, its association with our scenarios, the theoretical consideration of scenario impacts, and the related literature. Next follows the integrated CGE framework along with the data as well as the sectoral and regional resolution of the model. Scenario specification precedes the presentation and discussion of simulation results. The last section concludes the paper.

2 Background and Related Literature

2.1 Background

The term bioeconomy is defined differently in the literature. The EU defines bioeconomy as "the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy…" (EUROPEAN COMMISSION, 2012).[5] This definition embraces strategies that involve the entire supply chain from the production and utilization of biological resources to the production of final products (WESSELER and VON BRAUN, 2017) and may involve one or a mix of the four bioeconomy transition pathways (TPs) that have been identified by DIETZ et al. (2018): (TP1) replacement of fossil fuels by bio-based raw materials; (TP2) productivity increase of sectors producing bio-based products; (TP3) productivity increase of sectors utilizing bio-based materials; and (TP4) productivity increase of sectors relying on biological principles and processes (biomimicry) to produce environmentally friendly products. The TP2 and TP3 are both emphasized by the bioeconomy strategies of the EU and its member states.

The EU bioeconomy strategy identifies the increased productivity in biomass production as crucial for an increasing supply of raw materials. As almost 27% of the biomass in the EU originates from agricultural biomass (THE EUROPEAN COMMISSION'S KNOWLEDGE CENTRE FOR BIOECONOMY, 2019), several efforts are ongoing to increase productivity in this sector. Applications of technologies that use recently developed autonomous agricultural robots to minimize input use in the farming process are major promising advances (SHANG et al., 2021). Agricultural robots utilize artificial intelligence and cloud computing to support more efficient farming processes (TORKY and HASSANEIN, 2020; KLERKX et al., 2019). Depending on the type of biomass product and farming system, both partial and total factor productivity (TFP) improvements are promised. For example, a

[4] The European NUTS (in French: *Nomenclature des unités territoriales statistiques*)-2 system classifies regions into different administrative levels.

[5] In the German national bioeconomy strategy FEDERAL MINISTRY OF EDUCATION AND RESEARCH (2020), it is defined as "*the knowledge-based production and utilization of renewable resources in order to provide products, processes and services in all economic sectors, within the context of a future-capable economic system*".

small weeding robot used independently from other types of machinery in organic farming saves more labor than capital. Smart decision support systems that aim to optimize the spatial distribution and timing of fertilizer or pesticide application most certainly improve the partial productivity of those inputs and land productivity as long as management-related yield gaps still exist. New technologies in breeding like automated phenotyping promise to accelerate the development of new varieties (SHAKOOR et al., 2017) and support a continuing strong contribution of breeding to increases in land productivity (QAIM, 2020). The specific type of technical progress thus differs across related innovations. While there is no particular study evaluating the productivity and the input saving impact of these technologies, O'MAHONY and TIMMER (2009) and MCKINSEY GLOBAL INSTITUTE (2017) estimate that an additional annual growth of labor productivity of 0.6% is attainable from the advancements in the information and communications technologies. Others (ESCOBAR et al., 2018; JAFARI et al., 2020) see an additional 0.5% annual increase in partial productivity of agricultural inputs due to the ongoing technological advancements as a reasonable assumption. Due to the uncertain nature of the technologies that can be partially input-saving or neutral, this study assumes an annual increase by 0.5% in Hicks-neutral productivity in the primary agricultural sector in the EU above its historical growth (biomass expansion scenario).[6]

The EU bioeconomy strategy also identifies the increased conversion efficiency of bio-based materials in the sectors utilizing these inputs. In this respect, the chemical industry is one of the major destinations in which biomass inputs from agriculture can be utilized to produce bio-based products (DEJONG et al., 2020).[7] The EU has the second-largest chemical industry in the world, contributing 16.9% of the world's chemical sales in 2018, with Germany generating the largest share (31.8%) of the EU's chemical revenues (THE EUROPEAN CHEMICAL INDUSTRY COUNCIL, 2020). A large portion of the chemical sector, organic chemicals (chemicals that have organic carbon and hydrogen in them) constitute above 80% of the chemical sector (RAVET et al., 2016). This includes organic basic chemicals, pharmaceuticals, as well as plastic and rubber products. The bio-based components of organic chemicals in the EU have been increasing, whereas their bio-based share constitutes 6% of the overall chemical industry and 12% of organic chemicals (RAVET et al., 2016). This suggests a share of 4.8% of the biomass in the chemical industry at the EU level. However, the target of the Bio-based Industries Consortium (BIC) in the 2017 Strategic Innovation and Research Agenda is to increase the share of bio-based or renewable feedstock to 25% of the total volume of organic chemicals used by the chemical industry in 2030. To increase the biomass share in the refinery sector, the more efficient conversion of agricultural biomass in the chemical industry – by the development of highly efficient and cost-effective processing of biological feedstock into a range of bio-based products – is promising (NONG et al., 2020; ALSTON et al., 2009).[8] As these technologies intend to improve the conversion efficiency of biomass, they are assumed to increase the partial productivity of intermediate biomass inputs. NONG et al. (2020) suggest a 1.5% increase of conversion efficiency of biorefineries on an annual basis in addition to the historical trend as a reasonable rate due to related Research and Development (R&D) investments. This projection motivates our third scenario: increased conversion efficiency (biomaterial expansion scenario), where the conversion efficiency of biomass input in biorefineries increases by 1.5% on an annual basis above its historical trend.[9]

Technological advancements have both direct and indirect (spillover) effects on output and factor markets through both demand and supply side linkages. The impact of technological advances on sectoral outputs and resource allocation among competing activities is uncertain. A technology that aims to improve the productivity in agriculture (biomass expansion scenario) may reduce the input per unit of output produced in agriculture (the first-round effect which is often labeled as the engineering effect) and the indirect impact (also known as rebound effect), which refers to the economic responses that might reinforce, (partially) compensate, or even overcompensate the

6 Note that the TFP historical trend is reflected in the business as usual scenario.

7 The roadmap for a resource-efficient Europe sets a framework for the actions to develop a sustainable economy by 2050 and sets out a vision for the structural and technological change needed to be achieved by 2050 (EUROPEAN COMMISSION, 2011).

8 European Commission also sees the potentials to simulate the further use of biomass in chemical industry through demand side measures such as those market and command and control policies to boost the demand for biochemicals (see ESCOBAR et al., 2018).

9 The historical trend is captured by the business as usual scenario.

direct impact. This results in the relocation of resources across competing activities and affects the sectoral outputs. The rebound effect depends mainly on the demand-price elasticity of agricultural output.[10] If the demand price elasticity is larger than one, we may expect higher demand, higher output production, and higher demand for primary factors used in this sector (land, labor, capital, etc). Likewise, a technology that increases the conversion efficiency of biomass in the biorefinery sector (biomaterial expansion scenario) can increase or decrease the demand for biomass intermediate inputs and therefore increase or decrease the demand for biomass in agriculture and the resulting land demand. The research on rebound effects does not provide clear results because many general equilibrium effects are involved to determine the equilibrium outcome for price and quantity of agricultural outputs. While rebound effects are undisputed in the literature, the complexity of these second-round effects and the approach to detect these effects could potentially explain the diversity of estimated rebound effects ranging from a few percentages to 100% or more (Jevons' paradox, Khazzoom-Brookes postulate) (BLEISCHWITZ et al., 2011). Moreover, biomass used in bio-based products are also used in competing activities, including feed and food production, leading to a "biochemical-food" dilemma, where an increase in biomass use in one activity curbs other competing activities that use biomass intermediate inputs as well.

2.2 Related Empirical Literature

In the context of the bioeconomy, empirical studies on the analysis of transformation pathways are scarce. Related to the analysis of the *TP1*, ANDERSON et al. (2008) estimate the economic impact of an increased productivity in global cotton industry using GTAP (Global Trade Analysis Project). They find that adoption of genetically modified cotton increases production and welfare. GUNATILAKE et al. (2014) simulate a 1% annual growth of agricultural productivity over the period 2010-2030 with a focus on India. They highlight the resulting bioeconomy expansion, i.e. biodiesel expansion, and greater national self-sufficiency in food and energy, which in turn leads to higher incomes, employment rate, and lower greenhouse gas emissions. GHOSH et al. (2016) use a recursive dynamic CGE model and simulate the impact of technological change on the production cost of maize and wheat in India over the period 2015-2030. Their analysis shows an increased food production and economic growth. MUKHOPADHYAY et al. (2018) use GTAP model to estimate the impact of productivity advancements in Chinese agriculture and conclude this strategy as an important element in reaching grain self-sufficiency targets in 2030 and 2050. STURM and BANSE (2021) simulate the impact of various degrees of improved productivity in agricultural production over 2015-2050. They use the Dynamic CGE model MAGNET (Modular Applied GeNeral Equilibrium Tool) and show that this pathway expands the agricultural cropping activities, and if the production of bio-based products expands, the increased productivity mitigates the trade-off between the use of biomass in food and other activities producing bio-based products.

Related to the analysis of TP3, LEE (2016) uses the dynamic GTAP model to simulate the impact of decreasing bio-based production costs in Asian countries and shows the overall economic growth of the countries but the changes in the composition of output activities over the period 2014-2050. VAN MEIJL et al. (2018) perform a recursive dynamic CGE assessment of the macro-economic effects of expanding the Dutch bioenergy and biochemical sectors until 2030 and highlight the potential income growth. NONG et al. (2020) employ an integrated global CGE modeling approach and show the increased pressure on land resources due to reducing biomass conversion costs for global biochemical production by 1.5% annually until 2050.

None of the above studies consider the regional impact of transformation pathways or the global and regional medium- and long-term drivers of economic changes in their analysis. Only some of the above-mentioned studies (e.g. NONG et al., 2020) consider other complexities such as detailed treatment of intermediate and primary factor uses in the agricultural as those in GTAP-AGR (AGR for "agriculture") and GTAP-AEZ (AEZ for "agro-ecological zone").

3 Modeling Approach

Simulating the effects of bioeconomy transformation policies, in particular via technological improvements, requires models that consider multiple aspects of an economy. These aspects include global and regional drivers of change, relationships between input and output markets and their linkages with bioeconomic

[10] Rebound effects are often estimated as the negative of own-price elasticities.

policies, as well as the linkages between domestic and international markets (ANGENENDT et al., 2018). Integrated Assessment Models (IAMs) possessing both biophysical and economic components are the most comprehensive tools to identify both the economic and biophysical impacts of transformation pathways (DOELMAN et al., 2018). The model type addressing economic aspects in many IAMs are CGEs. These models consider the interlinkages between and within regions and markets and are widely used for ex-ante economic impact assessment of a wide variety of policy or (economic) structural changes.[11] CGEs can also be extended in different ways to capture the elements of bioeconomy pathways. Our modeling framework presented below is an integrated CGE framework that considers different aspects of bioeconomy pathways.

3.1 The Integrated CGE Framework

We use the modular platform for CGE modeling "CGEBox" (BRITZ and VAN DER MENSBRUGGHE, 2018), which takes the standard GTAP model (CORONG et al., 2017)[12] as its core, expanding it by various features that are especially important for this study. We briefly explain the features that we add to the standard GTAP model and provide the details in Online Appendix B. We incorporate features of GTAP-AGR (KEENY and HERTEL, 2005) that - compared to the standard GTAP - allow more flexibility in the substitution of the intermediate inputs in animal feed and in the transformation of mobile factors (labor and capital) across production sectors. We incorporate elements of GTAP-AEZ (HERTEL et al, 2009) that differentiates land by agro-ecological zones (AEZs) characterized by climate and soil types. This extension allows considering heterogeneous lands (different AEZs) where the total land use of each activity in each region is a *constant elasticity of substitution (CES)-aggregate of land use in different AEZs*. In each AEZ, the total available managed land, which is assumed to be fixed, is allocated across individual land use activities using a nested constant elasticity of transformation (CET) function as in Figure B2 in Online Appendix B. This demand and supply structure for land does not allow land inputs to move freely among individual competing activities and this has implications on agricultural activities as a source of biomass production. We *split the supply side of the model into the sub-national resolution to consider differences in regional input endowments and output composition. A CET function allows transformation of national primary factors to different NUTS-2 regions, while a CES function defines the national output as a composition of the NUTS-2 level outputs* (JAFARI et al., 2020).

To make the model dynamic and also allow for the construction of baseline trend for the dynamic analysis, we employ the (augmented) GTAP-based Recursive Dynamic Economic Model (G-RDEM) (BRITZ and ROSON, 2018; BRITZ et al., 2019). The construction of the baseline trend captures the impact of the global and regional drivers on the national and regional economies over years. In this respect, we *incorporate features of the recursive-dynamic G-RDEM model variant (*BRITZ and ROSON*, 2018) that* allows the construction of a long-term national baseline trend *based on the projected economic growth for each global region according to SSP2 pathway. G-RDEM first adopts the per capita economic growth for all countries as exogenous and computes* the necessary changes in total factor productivity across sectors and over the years in all nations to make this economic development happen. Next, the TFP parameters are fixed at their computed value for every year of a model run to generate the baseline trend for economic variables. During the baseline generation, the input-output coefficients (the share of inputs in the production of each output) are also updated as a function of TFP and relative prices of inputs. *The extension to project national-level variables/parameters to regional production structure follows the augmented G-RDEM (*BRITZ *et al., 2019). The methodology* is based on identifying the possible divergence path of the regional economic structure from the national path.[13]

[11] While also partial equilibrium models are used for the analysis of transformation pathways (LAURI et al., 2014), these models have only limited sectoral coverage and therefore do not consider the economy-wide feedbacks to the sector subjected to policy changes. Another widely used approach to analyze the (sustainability) impact of measures promoting bio-based products is Life Cycle Assessment (LCA) (TABONE et al., 2010; WEISS et al., 2012). LCA often relies on a detailed process description but analyzes a given value-chain in isolation from other economic activities.

[12] See Online Appendix B for the explanation of the standard GTAP model.

[13] This can be explained by the theories of regional economic growth and the new economic geography. The reason for the possible divergence path is the heterogeneity related to the differences in sectoral compositions of regional economies, differences in the region's primary factor endowments, and other factors explain-

Table 1. Share of intermediate inputs in output of economic activities in Germany

		Economic activities							
		Total output	Crop	Livestock	Extraction	Processed food	Other manu-factures	Chemicals	Services
Intermediate	Total intermediate demand	52.45	51.89	52.73	49.21	76.46	70.23	64.13	42.25
	Crop	0.41	1.37	7.29	0.75	9.71	0.01	0.16	0.06
	Livestock	0.33	0.12	0.64	0.12	9.38	0.00	0.06	0.01
	Extraction	1.77	0.27	0.34	8.28	1.05	4.54	1.17	0.60
	Processed food	1.15	0.08	14.82	0.00	18.62	0.02	1.68	0.61
	Other manufactures	16.23	6.82	3.09	15.93	4.80	42.08	9.84	6.07
	Chemicals	3.40	7.93	3.37	1.20	2.48	3.37	27.71	1.29
	Services	29.16	35.30	23.17	22.94	30.41	20.22	23.53	33.62

Source: GTAP 10 database

In this respect, the augmented G-RDEM defines regional TFP as a function of region-specific variables and their deviations from the national average: the share of aggregate sectors in these regions' gross value added, the square of this share, the ratio of this share in each region with respect to its national average, regional population and its square, and the difference between the regional and national population growth. The parameters of these functional relationships are estimated econometrically by BRITZ et al. (2019). Once the TFP trend at the regional level is constructed, their annual changes are introduced as exogenous shocks to the model simulating the regional-level production variables.[14]

3.2 Sectoral and Regional Resolution

Against the modeling framework, we use the GTAP 10 database (reference year 2014) comprising 65 sectors and 141 regions. We aggregate all regions to four major regions: Germany, the Rest of the EU14 consisting of the old EU members minus the United Kingdom, the Rest of the EU27 countries, and the Rest of the World (ROW). Germany is further disaggregated to NUTS-2 levels, whereas the breakdown of the production side of all sectors to regional NUTS-2 level is based on the data from Eurostat (the Statistical Office of the European Union). The biomass sectors in this study are the primary agricultural activities that provide inputs to chemical industries i.e. basic chemicals, pharmaceuticals, and plastic and rubber products. For reporting purposes, we aggregate all crop products as a conventional "biomass" sector[15], and all the three chemical industries into an aggregate "petrochemical" sector.[16]

Since we focus on the impacts on Germany, we present a snapshot of the German economy at the aggregated level in 2014 in Table 1. Crop products (primary agriculture excluding livestock) represents a small (0.41%) share of total economic output, and are mainly used in the livestock (7.29% of total costs) and processed food industry (9.74% of total costs) apart from its own sectoral use. Crop products also provide a small share (0.16%) of total production costs in the chemical sectors. Nonetheless, as shown in the table, the cropping sector uses the outputs of all economic activities and contributes to all sectors, thereby sustaining both downstream and upstream linkages with the rest of the economy.

3.3 Scenario Specifications

We consider three scenarios for our simulations (Table 2). The first is a baseline following the SSP2 projection of the global economy, in particular the quantified GDP and population associated with this projection at national levels. We obtain this information for the period up to 2050 (*RIAHI* et al., 2017),[17] available online from the International Institute for Applied Systems Analysis' (IIASA) SSP Database. Specifically,

ing the income differential of regions. These include agglomeration externalities, external (dis)economies of scale, inter-regional productivity spillovers, and other dynamic learning effects.

[14] The regional input-output coefficients at the regional level follow the national structure.

[15] Due to the purpose of our study, we do not consider biomass from forestry.

[16] See Table C1 in Online Appendix C for the GTAP and model sectors.

[17] The projected GDP and population are available for the period up to 2100.

Table 2. Scenarios layout

Scenarios	Technical implementation
Baseline (1)	Total factor productivities and conversion efficiencies in all economic sectors and in all countries follow historical patterns. These changes are based on the exogenously projected GDP growths from SSP2 and other factors showing disproportional changes in (total and partial factor) productivities across sectors.
Biomass expansion (2)	Baseline + Increase in total factor productivity in crop production activities by 0.5% annually in EU countries
Biomaterial expansion (3)	Baseline + Increase in conversion efficiency of biomass products into bio-refinery products by 1.5% annually.

Source: own construction

we obtain the projection of GDP per capita and population by age group and use these projections in G-RDEM to update the national economic structures, including the TFP, input-output coefficients, and cost share parameters. Subsequently, the augmented G-RDEM breaks down the changes at the German national level to regions based on the methodology explained above. Accordingly, the baseline scenario reflects the historical changes of economic variables including the productivity of all sectors in all countries at the national level and for Germany at the regional level as well.

The second scenario (biomass expansion) increases the TFP of biomass production by 0.5% *annually* in all the EU countries from 2020 to 2050 as motivated in the background section. The third scenario (biomaterial expansion) increases the conversion efficiency of biomass production in the chemical industry by 1.5% annually. We introduce both counterfactuals on the top of the baseline scenario, that is, TFP and conversion efficiency increases are above increases in productivity and conversion efficiency parameters from historical extrapolations already reflected in the baseline.

4 Results

4.1 Insights from the Baseline Scenario

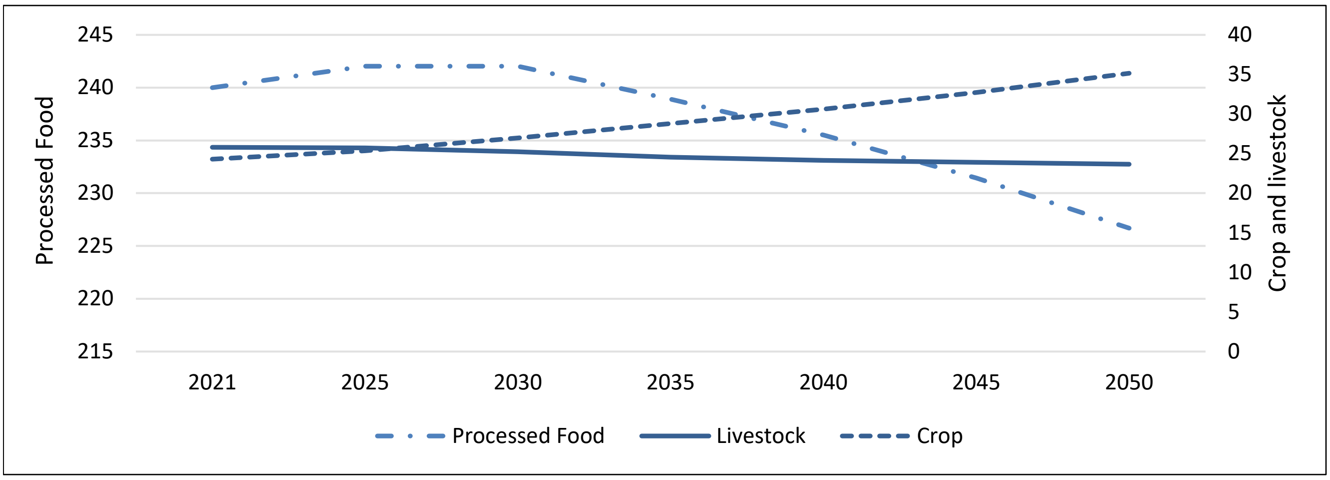
We first simulate the changes associated with the exogenously projected GDP and population growth across countries from SSP2 pathway (Figure C1 in Online Appendix C). While exogenous projections show an average annual growth of 1.2% in GDP in Germany,[18] our simulations reflect different growth paths for different economic activities because sectoral productivity, as simulated by G-RDEM, develops differently along the growth projections and each sector has different interlinkages with other economic sectors. The share of the agri-food sector in total activities declines from 6.3% in 2021 to 4.5% in 2050 because in high income countries TFP growth in agri-food sector from historical extrapolations are lower than average TFP growth across all economic activities. Trends of production in agri-food subsectors are presented in Figure 1. Crop activities are projected to grow by 0.94% annually, but the share of cropping activities in total economic output will decrease. A negative growth is projected for the livestock sector (-0.38%) and processed food (-0.25%); the contraction of these sectors in the long-run is mainly due to the relative reduction of German TFP in these sectors compared to world average TFP.

Improved productivity in the agri-food sector along the growth projections implies that the price (unit cost of production) of agri-food products is likely to decrease, mainly in early years, by about 8-12% (Figure 2). Land constraints are mainly responsible for the U-turn pattern around 2030. The changes in output prices also have consequences on trade in the agri-food sector (Figure 3). Germany still remains a net importer of crop products, with some increase in the export/import ratio. The reduction in productivity in the processed food sector relative to the ROW results in a decrease of this export/import ratio. The contraction of the processed food sector, in turn, reduces the demand for imported livestock products, and consequently, the export/import ratio for livestock goes up.

Figure 4 shows the percentage changes in the production of crops at the regional level under the baseline scenario across the years 2030, 2040, and 2050 as compared to the year 2021. Crop production activities are likely to grow up to 20% across regions by 2030, where the eastern regions of Germany show higher potential to grow. Growth rates are projected to more than double until 2040 across the regions. By

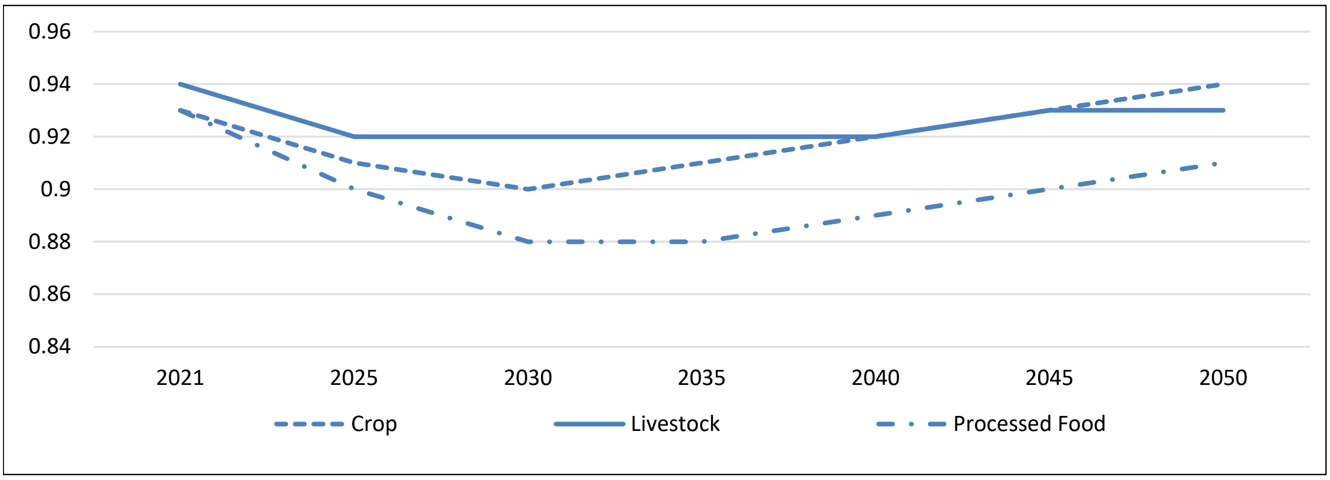
[18] Average annual growth rate = $[(\frac{\text{end year value}}{\text{start year value}})^{\frac{1}{N}} - 1\,] * 100$, where N is the number of years.

Figure 1. Trends of agri-food production (in bill. USD) in Germany in the baseline scenario



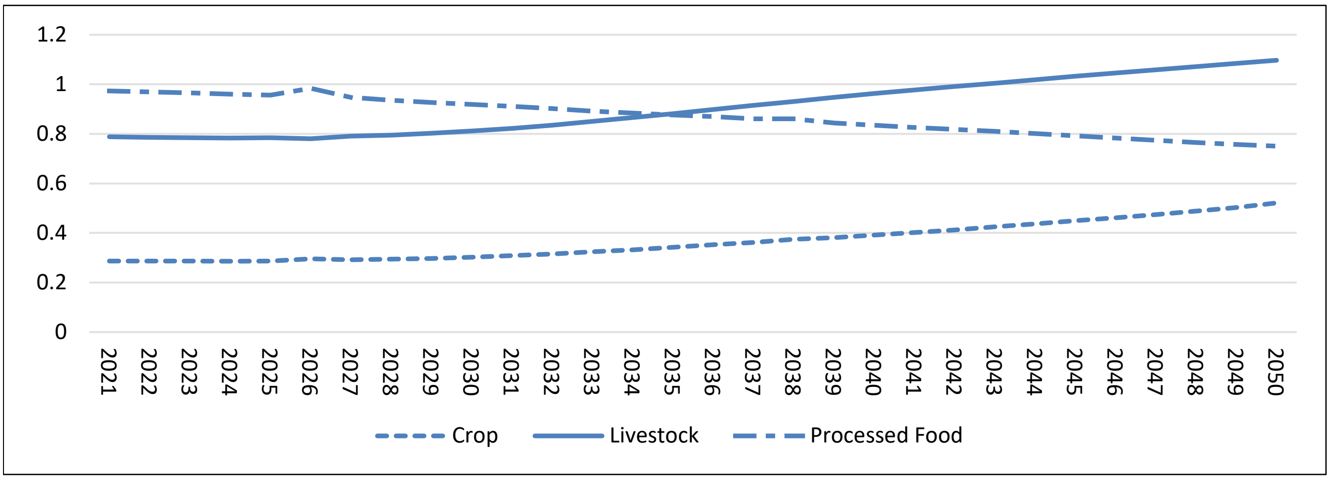
Source: simulation results

Figure 2. Output price index in agri-food products in Germany in the baseline scenario



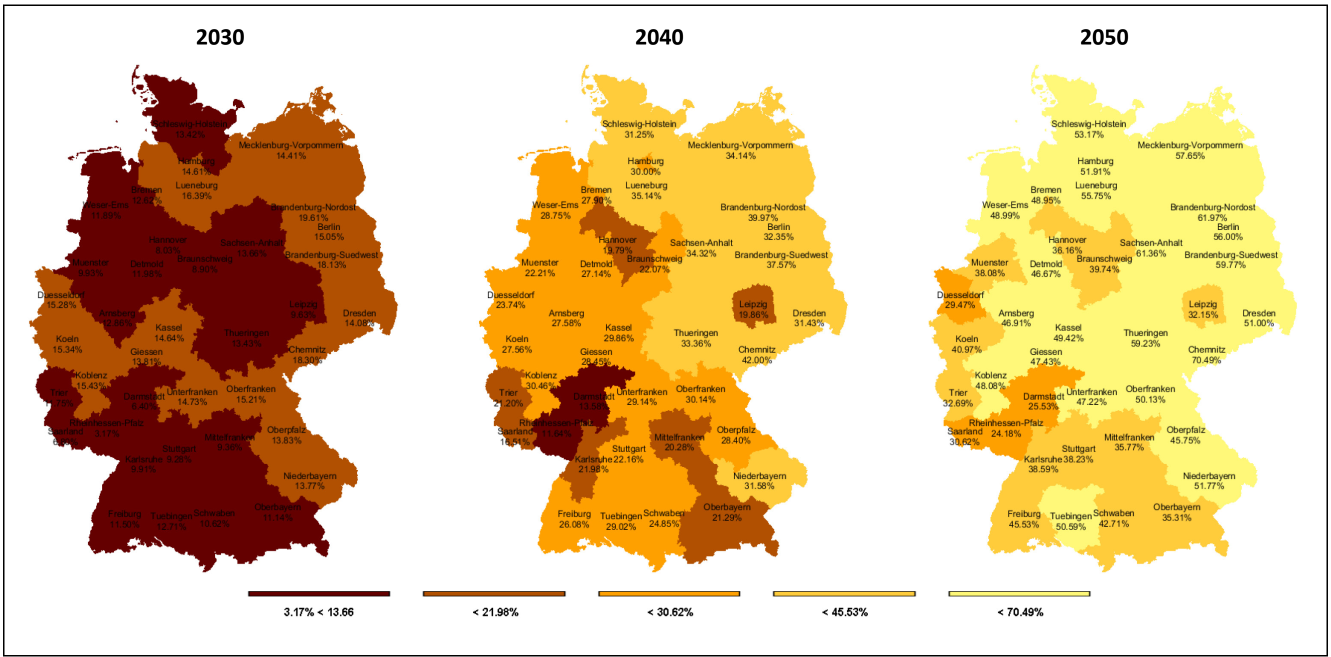
Source: simulation results

Figure 3. The impacts on agri-food trade (the ratio of export/import) in the baseline scenario



Source: simulation results

Figure 4. Percentage crop output change compared to 2021 under the baseline scenario



Source: simulation results

2050, the output growth rates in the regions have at least tripled, but the growth rates in the 2040s are lower than those of the 2030s. This implies an inverse U-shaped growth whereby the growth rate is increasing in early stages but until 2050 – due to resource constraints – the growth rate decreases.[19]

The heterogeneous impacts are due to several reasons reflected by the mechanisms of the augmented G-RDEM, whereby regions are likely to experience substantial differences in their productivity growth both across time and sectors. First, the changes in sub-national TFP in agriculture are driven by the historical convergence/diversion of regional output from the national average, because of which the eastern regions of Germany grow faster (Table 3) in a continuation of their catch-up process. Second, the composition of economic activities and endowments across regions differs. Third, population projections of regions, which determine labor availability in those regions, are different (Table C2 in Online Appendix C), thereby resulting in different output supply responses of regions. Our observations point toward the first reason as the most important one. The highest growth of productivity (Table 3) is projected for the regions in the eastern half of Germany, which historically had lower yields compared to former western Germany. This discrepancy was caused by the relative inefficiency of collectivized agriculture under socialism in Eastern Germany and has started vanishing in recent years, but this process is likely to continue for some decades. Up to 2050, the agricultural sector in parts of Germany (Rows 1-5) grows by more than 27%, which is only slightly above the projected productivity growth of the rest of the world (26.8%). Some other parts of Germany (Row 6-14) grow above the rest of the EU27 countries but below the world average. Many other regions are projected to grow within the range of 1.5% in Mittelfranken to 16.2% in Oberpfalz (see Row 15-32), and a small number of regions is predicted to experience a contraction in their productivity (Row 33-39).[20]

The pattern of the changes in land use under crop activities across regions also varies quite substantially (Figure 5).[21] The demand for cropland increases across all regions up to 2040. However, during the subsequent decade, the demand for cropland would recede to a level close to 2021 or even lower. The

[19] We note that the inverse U-shape is related to the output growth rate but not the level of output, meaning output is increasing at the increasing rate and then increase at the decreasing rate.

[20] A similar pattern can also be found in the manufacturing and services sectors.

[21] The changes of cropland in each region reflect the redistribution of the total available fixed stock of managed land across land use activities.

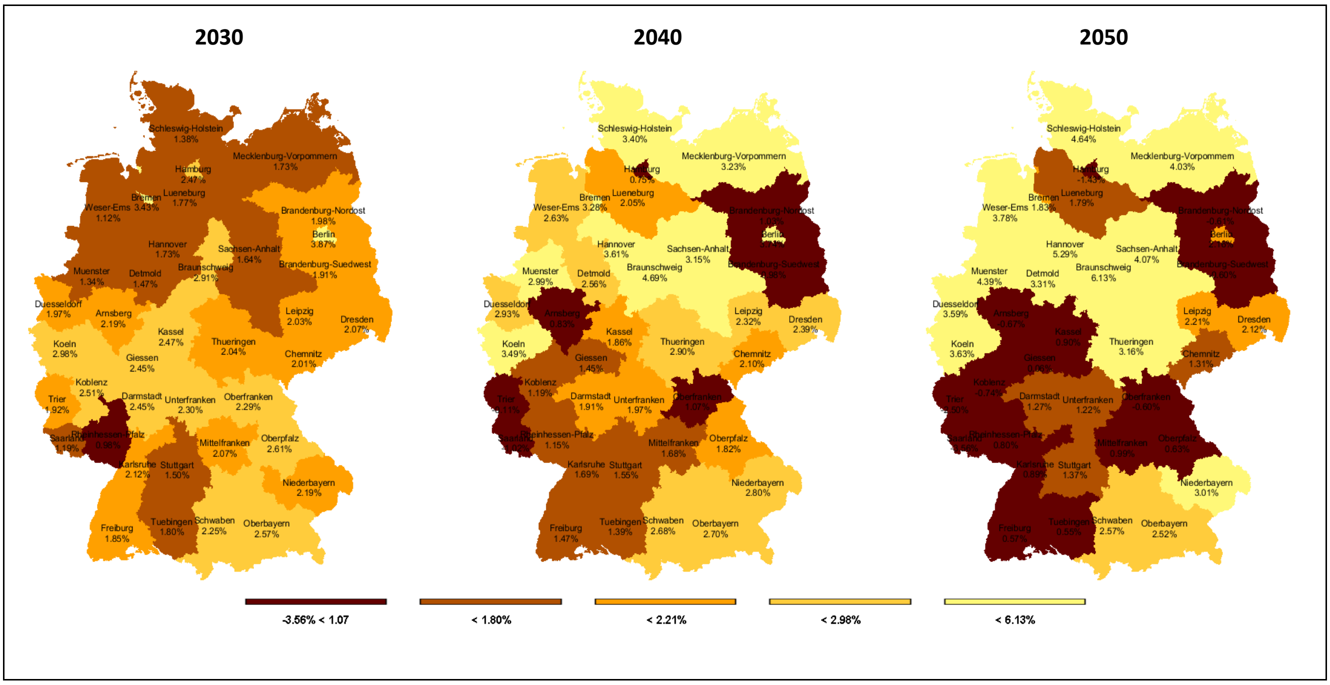
latter is evident in the case of Brandenburg, the northern part of Bavaria, and southwestern states. We observe two patterns of expansion across time (Table C3 in Online Appendix C): a steady expansion until 2050 (12 out of 39 regions) and whereon with the peak of the expansion either during the 2030s or 2040s (remaining 27 regions). The observed pattern depends on the pattern of output growth and the substitution of primary factors (land, capital, labor) across years. When the output effect dominates the input substitution effect, we expect an expansion of cropland use. If the substitution effect is the dominant effect and the inputs are substituted in favour of non-land inputs, a decline in cropland use is expected; otherwise, an

Table 3. Percentage changes in productivity compared to 2021 (baseline scenario)

		Agriculture			Manufacturing			Services		
		2030	2040	2050	2030	2040	2050	2030	2040	2050
1	Chemnitz	9.3	26.0	44.7	10.1	31.4	55.2	9.3	25.5	43.5
2	Sachsen-Anhalt	4.9	16.8	31.3	5.7	22.2	41.9	4.9	16.2	30.2
3	Brandenburg-Nordost	7.6	18.8	28.1	8.4	24.1	38.5	7.6	18.3	26.9
4	Mecklenburg Vorpommern	5.6	16.2	27.4	6.4	21.5	37.9	5.5	15.7	26.2
5	Thueringen	3.7	14.3	27.0	4.5	19.7	37.7	3.7	13.7	25.8
6	Brandenburg-Suedwest	6.3	16.6	26.1	7.1	21.9	36.5	6.3	16.1	24.9
7	Koblenz	6.4	15.5	24.2	7.2	20.7	34.7	6.3	14.9	23.1
8	Dresden	3.0	11.2	18.7	3.8	16.6	29.5	3.0	10.6	17.5
9	Unterfranken	4.9	11.8	18.7	5.7	17.1	29.1	4.9	11.2	17.5
10	Kassel	3.9	10.9	18.6	4.7	16.2	29.2	3.9	10.3	17.5
11	Lueneburg	3.6	11.9	18.4	4.4	17.2	29.0	3.6	11.3	17.2
12	Niederbayern	2.4	10.7	17.8	3.2	16.2	28.7	2.4	10.1	16.5
13	Oberfranken	2.7	9.1	17.4	3.5	14.5	28.0	2.7	8.6	16.2
14	Giessen	2.7	9.0	16.6	3.5	14.4	27.2	2.6	8.5	15.4
15	Oberpfalz	2.2	9.1	16.2	3.0	14.6	27.0	2.2	8.6	15.0
16	Detmold	0.9	7.1	14.6	1.7	12.6	25.4	0.9	6.6	13.3
17	Saarland	0.5	6.4	14.2	1.3	11.9	24.9	0.5	5.9	13.0
18	Weser-Ems	-0.7	6.1	13.3	0.1	11.6	24.2	-0.8	5.5	12.1
19	Trier	3.3	8.1	12.3	4.1	13.3	22.7	3.3	7.5	11.2
20	Braunschweig	0.2	5.5	12.1	1.1	11.0	23.0	0.2	4.9	10.9
21	Schleswig-Holstein	0.9	6.1	11.4	1.7	11.5	22.2	0.8	5.5	10.2
22	Arnsberg	0.0	4.9	10.7	0.8	10.4	21.6	0.0	4.3	9.5
23	Tuebingen	-0.9	4.1	10.1	-0.1	9.7	21.1	-0.9	3.5	8.9
24	Koeln	6.1	9.3	9.8	6.8	14.3	19.8	6.0	8.7	8.7
25	Schwaben	-1.2	3.7	9.4	-0.3	9.3	20.4	-1.2	3.2	8.1
26	Freiburg	-1.7	2.2	7.3	-0.9	7.8	18.4	-1.8	1.7	6.1
27	Rheinhessen-Pfalz	-1.8	2.1	7.3	-1.0	7.6	18.2	-1.8	1.6	6.1
28	Muenster	-1.7	2.1	7.0	-0.9	7.6	18.0	-1.7	1.5	5.8
29	Stuttgart	-0.9	3.2	6.7	0.0	8.7	17.8	-0.9	2.6	5.4
30	Hannover	-1.6	1.5	6.0	-0.8	6.9	16.9	-1.6	0.9	4.8
31	Karlsruhe	-2.6	-0.4	2.9	-1.8	5.1	13.9	-2.7	-1.0	1.7
32	Mittelfranken	-3.5	-1.8	1.5	-2.6	3.7	12.6	-3.5	-2.4	0.3
33	Oberbayern	-2.2	-2.2	-1.4	-1.4	3.2	9.5	-2.3	-2.8	-2.6
34	Leipzig	-2.5	-2.0	-1.6	-1.7	3.5	9.2	-2.6	-2.6	-2.8
35	Duesseldorf	4.8	4.1	-2.1	5.6	9.2	7.9	4.8	3.6	-3.3
36	Bremen	-4.6	-4.4	-2.9	-3.8	1.1	8.0	-4.7	-5.0	-4.1
37	Hamburg	-4.8	-5.2	-3.7	-4.0	0.4	7.3	-4.8	-5.8	-5.0
38	Berlin	-5.7	-5.8	-3.9	-4.8	-0.2	7.2	-5.7	-6.3	-5.2
39	Darmstadt	-5.3	-7.1	-7.0	-4.5	-1.6	3.9	-5.3	-7.6	-8.2
40	Rest of World	13.1	20.2	26.8	12.6	20.4	28.3	8.1	13.3	18.5
41	ROEU14	4.3	10.6	16.8	6.3	15.4	24.7	3.6	8.8	14.0
42	ROEU27	4.6	10.7	16.4	6.4	15.2	24.2	3.7	8.7	13.7

Source: simulation results

Figure 5. Percentage change in cropland compared to 2021 (baseline scenario)



Source: simulation results

increase in cropland use is expected. Concerning the other primary inputs, we observe an increasing growth rate for capital and a decreasing one for labor (both low- and high-skilled labor) across all regions (Table C4 in Online Appendix C) where most of the changes would occur in the 2040s.[22]

4.2 Impact of Improvement in TFP in Crop Production

This scenario increases the annual growth rate of crop production, in contrast to the baseline scenario, from 0.94% to 2.13%, and as a consequence, it increases the share of crop activities within total agricultural production value (Figure 6). Both livestock production and food processing sectors increase their production compared to the baseline trend, but these sectors are still projected to experience negative growth in 2050 by -34% and -17% compared to -38% and -25% in the baseline (Figure 6).

The price (unit production cost) of crop products drops significantly by -25% by 2050 (Figure 7). This results in a decrease in the price of food and livestock because crop products are important intermediate inputs in the production of these commodities. The reduction in the unit costs of production of these sectors enhances the competitiveness of these sectors and therefore fosters the trade position of Germany in these sectors (Figure 8).

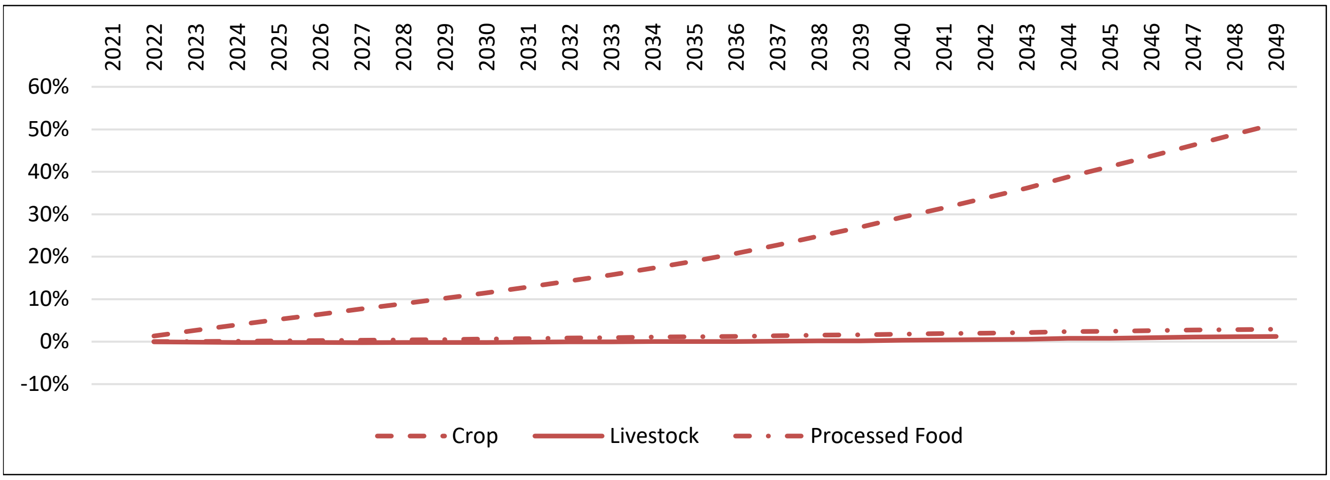
The percentage deviation in crop production from the baseline shows almost identical increases at the regional level (Figure 9, for years 2030, 2040, and 2050), but the differences across regions slightly widen over time. The magnitude of increases in regional outputs indicate a high elasticity of output with respect to the TFP improvement. Considering the cumulated average increase of TFP[23] in the years 2030 (6%), 2040 (12.7%), and 2050 (20%), crop output deviates more from the baseline with an average of 10-12%, 27-31%, and 50-57% in years 2030, 2040 and 2050, respectively. The highest increase is again observed in the Eastern regions, thereby indicating that elasticity of output with respect to productivity in these regions is higher and it increases over time.

The associated cropland use impacts are also significant (Figure 10), with increases from the baseline's cropland use by 0.57% (2030), 1.53% (2040) and 3.08% (2050) on average (see also Table C6 in Online Appendix C).

[22] Table C4 in Online Appendix C also summarizes the changes in total primary factor demand that is decreasing.

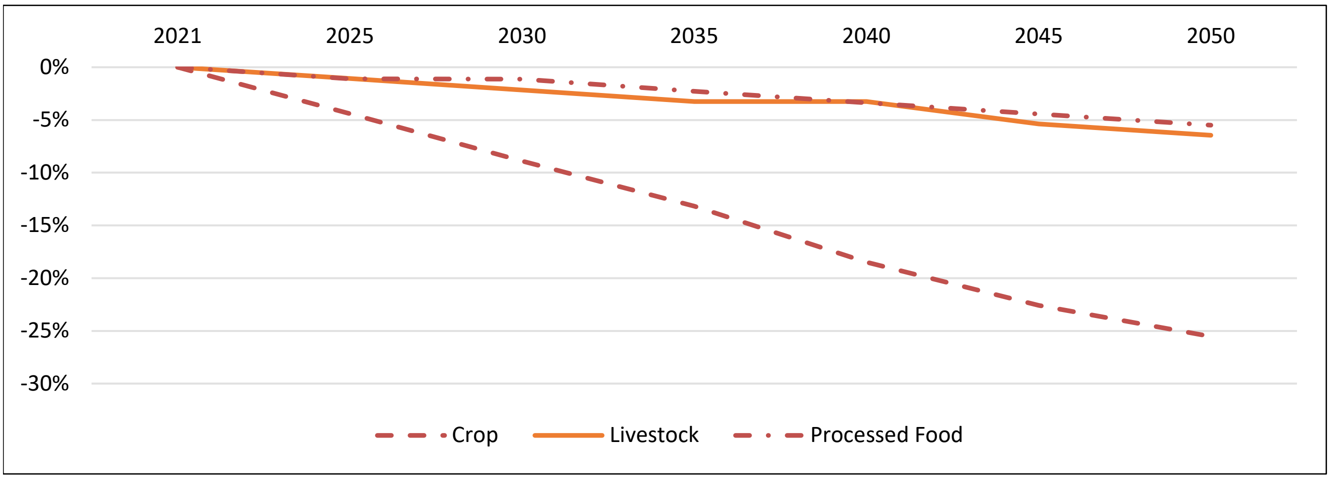
[23] $TFP_t = TFP_{2021}(1 + 0.05)^t$

Figure 6. Agri-food output under biomass expansion scenario (% deviations from the baseline)



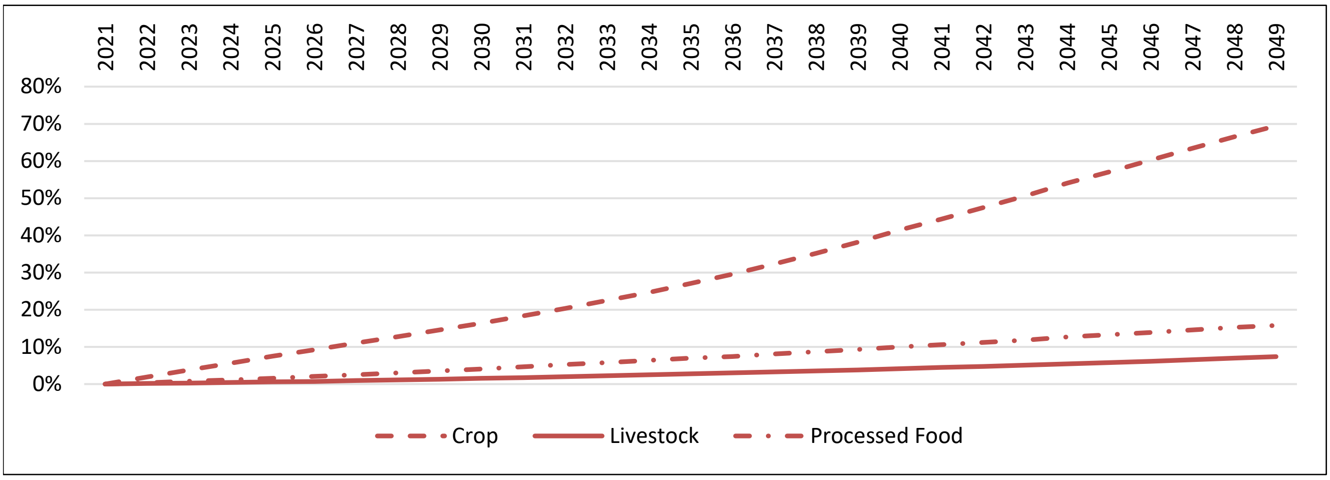
Source: simulation results

Figure 7. Prices under the biomass expansion scenario (% deviations from the baseline)



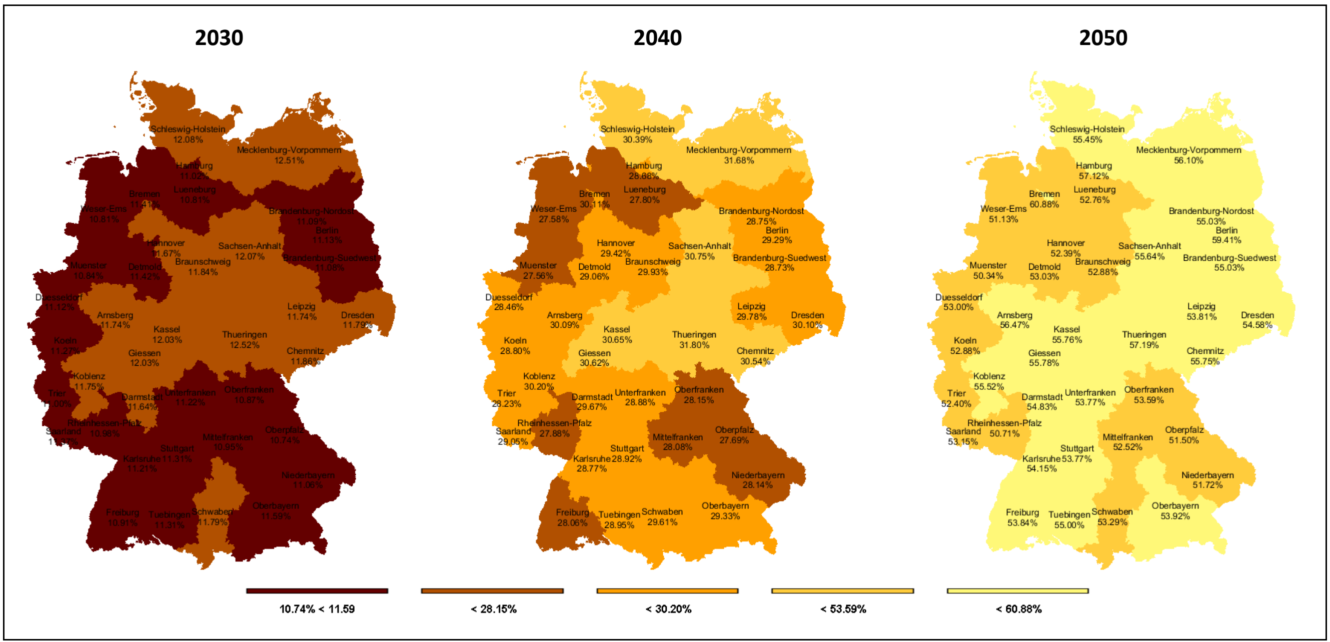
Source: simulation results

Figure 8. Export/import ratio under biomass expansion (% deviations from the baseline)



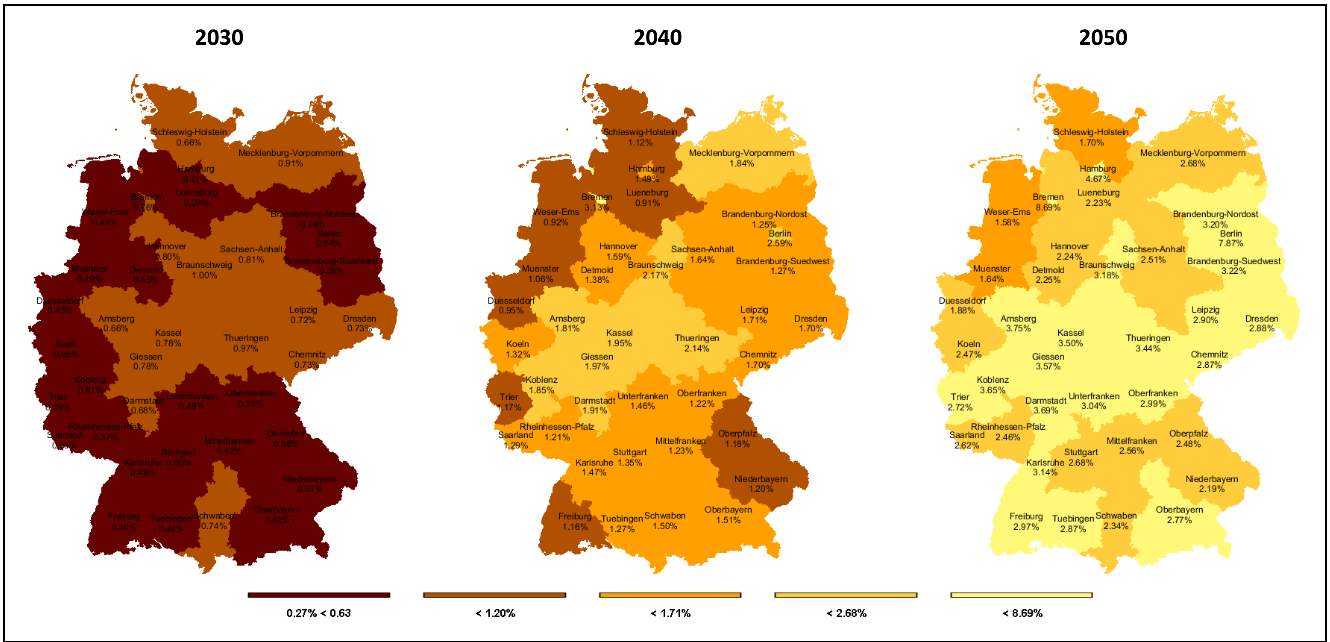
Source: simulation results

Figure 9. Crop output change under biomass expansion scenario (% deviations from the baseline)



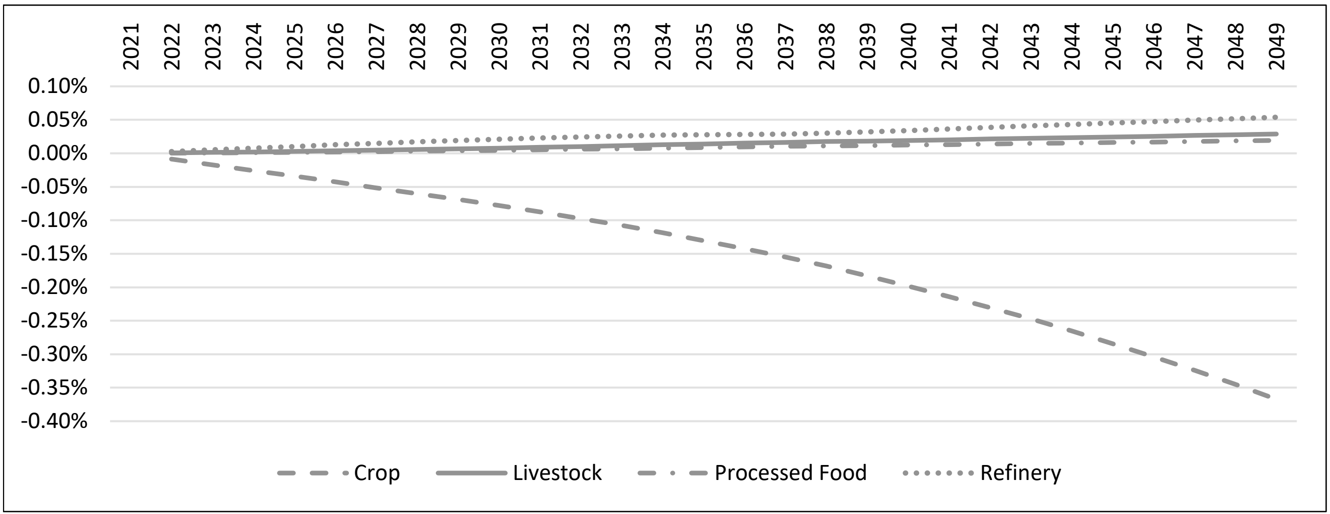
Source: simulation results

Figure 10. Cropland use under biomass expansion scenario (% deviations from the Baseline)



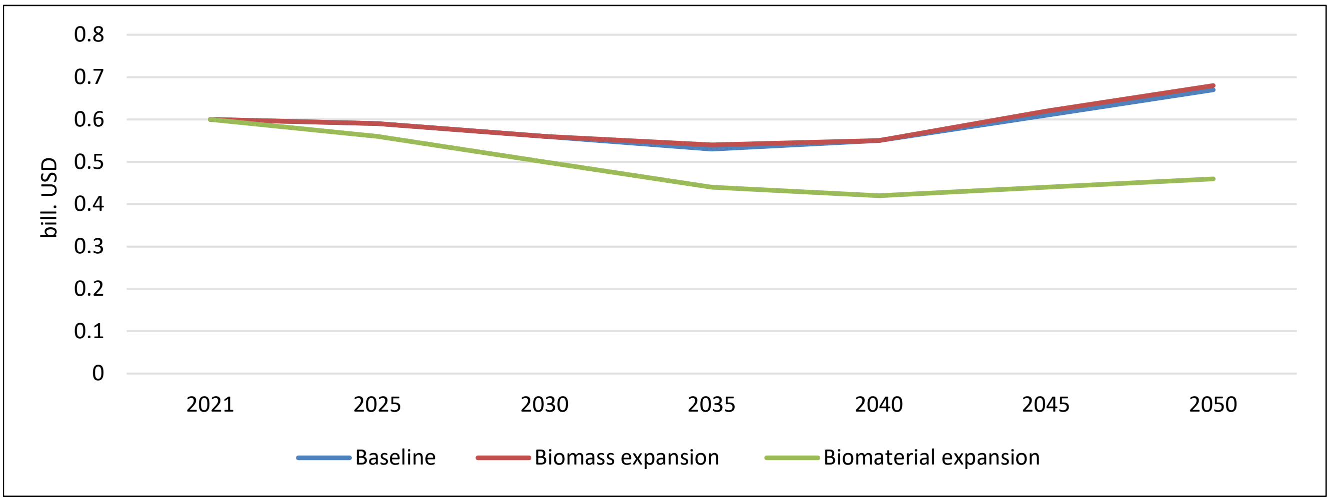
Source: simulation results

Figure 11. Output changes in biomaterial expansion (% deviations from the Baseline)



Source: simulation results

Figure 12. Utilization of crop outputs in biochemical sectors



Source: simulation results

4.3 The Impacts of Increased Biomass Conversion Efficiency

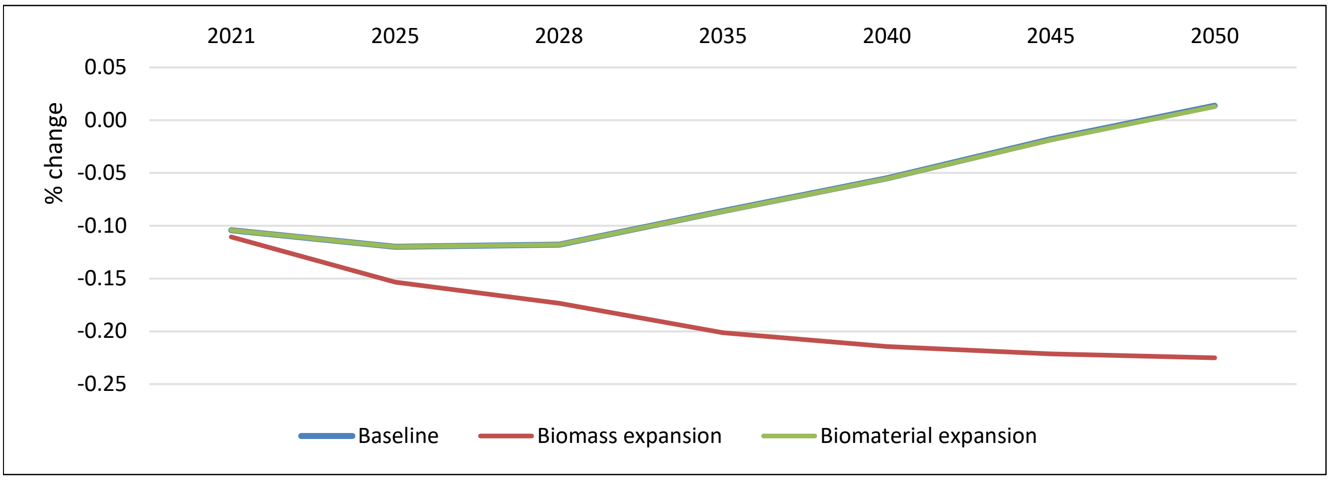
The increased conversion efficiency does not significantly increase agricultural production (Figure 11).[24] This is because agriculture products only constitute a small input share (0.16%) in the chemical sector (Table 2). Accordingly, it also has a minor impact on production in the refinery sector.

Nonetheless, improved conversion efficiency decreases the existing demand for biomass use from agriculture significantly (Figure 12) due to the first-round effect, i.e. the engineering effect. However, the price of biomass due to improved conversion efficiency is almost the same as in the baseline trend, which is why a rebound effect cannot be observed (Figure 13). While the increased domestic demand in agricultural output may foster imports, decreased prices overcompensate for this, thereby leading to an increase in the trade position in crop producing activities of Germany (Figure 14).

Only tiny differences compared with the baseline exist across regions (Figure 15), which reflect different intensities and crop cultivations pattern across regions. The impact on cropland use changes is also negligible (see Table C6 in Online Appendix C). The cropland use change diverges from the baseline's cropland use by -0.02% (2030), -0.06% (2040) and -0.12% (2050) on average across regions (Figure 10, see also Table C6 in Online Appendix C).

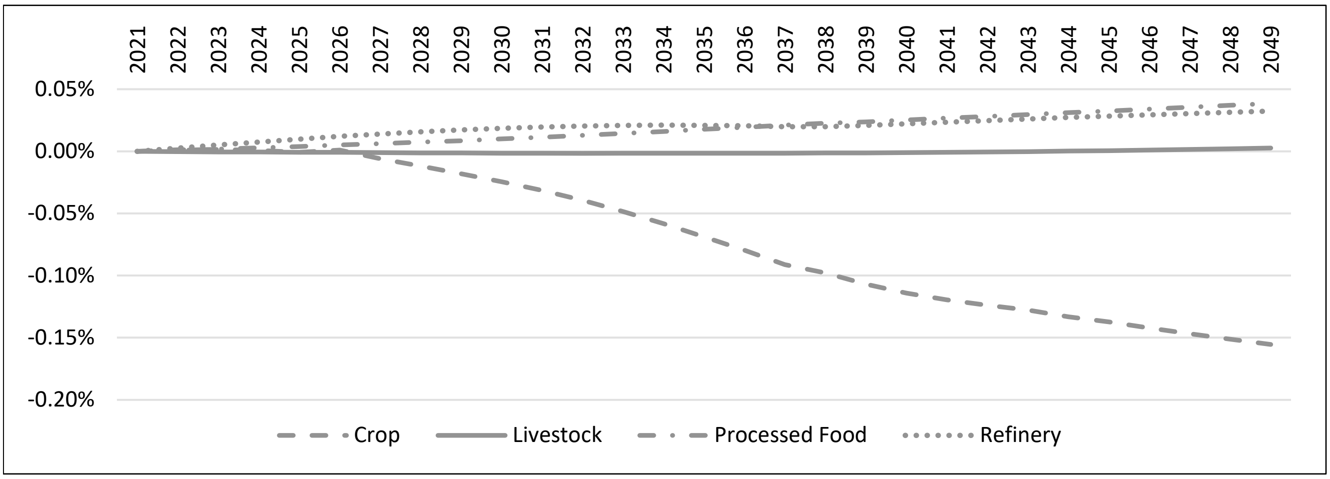
[24] This scenario does not significantly affect the production of the chemicals sector (Figure 14).

Figure 13. Price of biomass for biochemical use



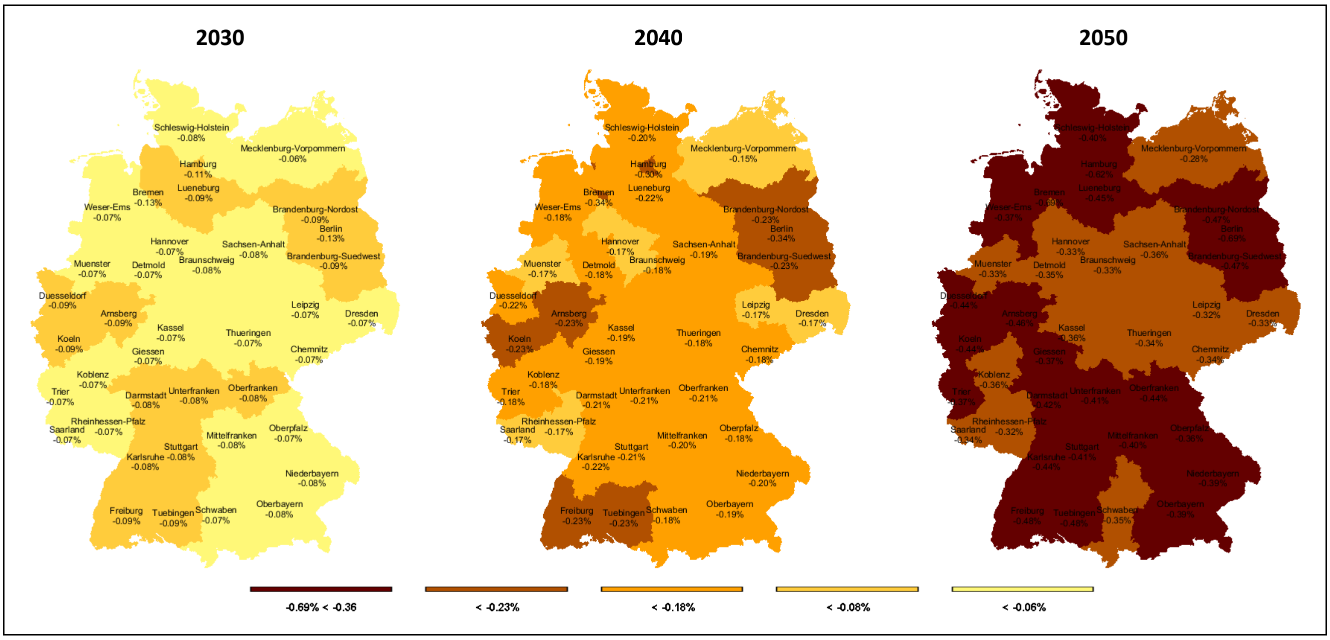
Source: simulation results

Figure 14. Export/import ratio under biomaterial expansion (% deviations from the Baseline)



Source: simulation results

Figure 15. Crop output under biomaterial expansion scenario (% deviations from the baseline)



Source: simulation results

To obtain additional insights, we also investigated a combined impact of increased productivity of biomass production and increased conversion efficiency of agricultural biomass in biochemical sectors on top of the baseline. We observe an impact similar to the improved productivity scenario on agricultural biomass, livestock, food production, and land use changes at national and regional levels. So, no specific interaction effects between the two scenarios occur and consequently the combined effect is dominated by the improved productivity scenario.

5 Conclusion

Transformation to a bioeconomy is one of the approaches of the EU to support a sustainable economy. In this study, we simulate scenarios related to different bioeconomy pathways up to 2050 using a regionally extended dynamic CGE model. First, we consider a global SSP2 scenario (the baseline scenario), where the global socio-economic changes follow extrapolations of historical trends, and the transformation to a bioeconomy is on a drip. Second, we simulate the impact of increased TFP of agricultural crop production in the EU by 0.5% annually on top of the baseline. Third, we model an increase in the efficiency of conversion of agricultural intermediate inputs to biomaterials in the biochemical sector of the EU by 1.5% annually on top of the baseline. We focus on the impacts of the three scenarios in Germany at both national and sub-regional levels.

The baseline shows crop activities continue to grow by 0.83% annually, which is lower than the average economic growth rate of 1.04%. Both livestock and processed food sectors contract at the expense of a higher production share of manufacturing and extraction sectors. The regional changes generally show the same direction of change but magnitudes of changes differ considerably across regions, with larger values in Eastern Germany. This is due to the regional variation in sectoral output composition and primary input endowments. Changes in cropland use follow different patterns across regions: upward, downward, and inverse U-shape trends, depending on the strength of output changes and substitution possibilities associated with the main drivers of demand for cropland.

Increasing the productivity of cropping activities reveals significantly larger crop production growth (2.3% annually), leading to an increased share of cropping activities in total economic output. Increased productivity mitigates to some extent the contraction of both livestock and food processing sectors. By 2050, the use of cropland across regions grows on average by 3.2% within a range of 1.6% to 9%. This comes mainly at the expense of land used for livestock production.

Increasing the conversion efficiency of agricultural products used as inputs for the chemical sectors lowers their demand, as these resources are then utilized more efficiently. A rebound effect is not observed due to the low share of agricultural biomass in the chemical sector's input portfolio. Consequently, this scenario shows no significant impact relative to the baseline, neither on crop production nor on chemical output.

Overall, our results indicate that ongoing efforts to improve the productivity of crop production are crucial for a successful bioeconomy transition. These efforts would help reduce resource competition between non-food and food biomass use, as well as the competition between crop and livestock production. However, our analysis also suggests that the introduction of technologies to improve conversion efficiency alone may not be enough to create a significant push for the use of biomass in the chemical industry. Additional developments, such as a fundamental transformation of technologies in the chemical industry or broader shifts in consumer preferences towards bio-based chemical output or strong financial or regulatory measures, would be required to enhance the use of biomass in the chemical sector and speed up the transformation. Nevertheless, any measure that increases biomass use would only be politically defendable if they go along with a strong productivity increase in biomass production.

Some limitations clearly apply: our simulation results are based on an annual percentage increase of productivity and conversion efficiency across all cropping activities and biomass uses. Future studies may better estimate the potential associated with novel technologies in both areas. In this study, we restricted the analysis to impacts of innovations on the bioeconomy transition. Other avenues of the bioeconomy transition may be induced by specific incentive-based policies or consumer demand changes, warranting separate scenario analyses. Moreover, the construction of the baseline for the dynamic simulations in this study is based on the assumption that important model drivers will merely extend historical patterns. The consideration of other possible SSPs and performing counterfactuals comparing to them can deliver further insights about possible bioeconomy futures.

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Acknowledgment

The authors would like to thank the two anonymous reviewers and the editor of the journal for their highly constructive and insightful comments that greatly improved this paper. The authors would also like to thank Wolfgang Britz, Till Kuhn, and Helena Engemann for engaging in valuable discussions. This study has received funding from the Ministry of Culture and Science of the German State of North Rhine-Westphalia under the project Transform2Bio, as well as from the European Union's research and innovation program under grant agreement No 817566 - MIND STEP and 101060765-CLEVER. The views expressed here are solely those of the authors' and may not in any circumstances be regarded as stating an official position of the funding agency.

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