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# Nitrogen Tax and Set-Aside as Greenhouse Gas Abatement Policies Under Global Change Scenarios: A Case Study for Germany

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## Abstract

The ambitious climate policy objectives of the COP21 agreement require the design and the implementation of effective and efficient policy instruments. The effectiveness and efficiency of agricultural abatement options depend on regional climate and natural conditions, changes in the global economy, global agricultural markets and regional agricultural production. Thus, the assessment of abatement options requires consideration of the global scale, the market scale and the regional producer scale. We investigate two abatement options discussed controversially in literature. Both have been partially applied to reduce environmental pollution from agriculture: a tax on nitrogen and the obligatory set-aside of agricultural land. Our study provides an assessment of the ecological effectiveness and the economic efficiency of both abatement options under different global scenarios. In our policy analysis we combine three applied policy simulation models to develop an integrated economic model framework. This model framework considers the global, the national and the regional scale and consists of the global general equilibrium model DART-BIO, the partial-equilibrium model CAPRI and the regional supply model RAUMIS. In the different global scenarios, the results show that both abatement options create relatively high marginal abatement costs and that the maximally reached abated greenhouse gas emissions represent only 15% of the quantity required to fulfill the policy targets. Compared to the obligatory set-aside option, the nitrogen tax is in both scenarios the more efficient policy. With respect to impacts on production and environment, a nitrogen tax is less forecastable than the obligatory set-aside option. Our study illustrates the relevance of considering global economic and market change in the assessment of producer-targeting environmental policies.

**Keywords** Greenhouse gas abatement · Environmental policies · Agriculture · Global scenarios · Integrated modelling

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# 1 Introduction: Importance of Abatement Policy Instruments

In December 2015, the parties of the Paris Conference (COP 21) agreed to limit global warming to an increase of 2 °C (Tobin et al. 2018; Ghezloun et al. 2017). Reaching this target requires the reduction of European Greenhouse Gas (GHG) emissions by 80–95% by 2050, as compared to 1990 (WBAE and WBW 2016).

In Europe, agricultural production accounts for more than 10% of the total emissions, with leading emitters in absolute terms France (18%), Germany (15%) and Britain (10%) (Allen and Maréchal 2017). In Germany, agricultural production accounts for 7% of total GHG emissions, i.e., 67 million tons carbon dioxide equivalent (M t CO<sub>2</sub>e) (excluding emissions from agriculturally used peat lands) out of 902 M t CO<sub>2</sub>e (UBA 2017). The abatement potential for German agricultural production is estimated at 23–24 M t CO<sub>2</sub>e/year with moderate climate protection, and at 40–44 M t CO<sub>2</sub>e/year with ambitious protection. Thus, it would account for a reduction of less than 2–5% of the total GHG emissions of 902 M t CO<sub>2</sub>e (WBAE and WBW 2016).

In order to exploit these abatement potentials, researchers and politicians require the design and assessment of ecologically effective and economically efficient abatement options. Assessing agricultural abatement options and their impacts on agricultural producers is challenging. In their production decisions, agricultural producers consider regional characteristics such as climate and environmental conditions, soil quality, and cultural and legal frameworks (e.g., Tilman et al. 2011). Furthermore, global signals influence producers' decisions, such as changes on agricultural markets, global economic and policy interventions (e.g., Porkka et al. 2017). These global drivers from markets and global economy are associated with uncertainties and include multi-faceted feedbacks between politics, markets, and the environment. The development of the global economic drivers (e.g., oil prices), environmental agreements (e.g., Paris Agreement 2015) or global policy targets (e.g., the Sustainable Development Goals) influence the impact of agricultural abatement options on producers' decision. Therefore, the assessment of agriculture-related abatement policies requires the consideration of global economic change, of the development of agricultural markets and regional agricultural production conditions.

Many studies investigate agricultural abatement options for different European countries. However, none of these studies considers the influence of changes on global drivers on the investigated abatement options. In our study, we consider global economic changes (e.g., agricultural prices) to analyze the ecological effectiveness, the efficiency and the impacts of two policy options to reduce environmental impacts: the market based policy instrument “nitrogen tax” and the command and control instrument “compulsory set-aside”.

In 1980 and 1990 the nitrogen tax was discussed as policy instrument to reduce nitrogen pollution in water bodies. In some northern European countries (Austria, Denmark, Finland, The Netherlands, Norway, Sweden) a fertilizer tax was (temporarily) applied (OECD 2017). In Germany, the expected low effectiveness of a nitrogen tax prevented its introduction. The expected inelastic price reaction raised the concern of high increase of nitrogen tax required to reach a sufficient effectiveness, which then would increase production costs and hurt the farmers' economic situation (WBAE and WBW 2016).

Although applied tax levels appeared to be too low for effective environmental impacts, some improvements were observed for groundwater quality in the Netherlands and Sweden (OECD 2017). Several studies consider the nitrogen tax as an effective

measure to reduce environmental impacts, including the reduction of ground water pollution and greenhouse gas emissions (e.g., Rougoor et al. 2001; Finger 2012; Neufeldt and Schäfer 2008).

In the history of the European Common Agricultural Policy (CAP) the measure set-aside has developed from a market regulation measure to an environmental measure. In 1988, the CAP introduced set-aside initially as a financially-compensated voluntary measure to decrease crop overproduction in the EU-15 Member States. The 1992 CAP reform changed the measure to a compulsory set-aside with monetary compensation. Since the compulsory set-aside did not target environmental objectives, the production of crops for industrial use was allowed on set-aside land. Nevertheless, the annual average of 10% fallow arable land created some landscape heterogeneity in intensively managed arable landscapes across much of Europe (Morris et al. 2011).

Herewith it created positive environmental impacts on biodiversity, reduction of diffuse pollution and soil erosion. Because of increased demand for agricultural products, prices and concerns for food security, in 2008 the CAP Health Check abolished the compulsory set-aside and thus lost the positive environmental impacts resulting from it. With the identification of new environment-oriented 'challenges' (e.g., climate change, water management and biodiversity), the CAP 2013 reform re-introduced the ecological set-aside, which targets the reduction of negative environmental impacts as a greening component. To retain the eligibility for the full amount of direct payments, farmers are required to use 5% of arable land as ecological set-aside.

Scientific literature discusses the nitrogen tax and set-aside controversially. On the one hand, scientific literature presents both options as ecologically effective policy measures (e.g., Kovács-Hostyánszki and Báldi 2012; Morris et al. 2011; Levin and Martin 2010; Matthews 2013; Rougoor et al. 2001; Finger 2012; Neufeldt and Schäfer 2008). On the other hand, some studies question the ecological effectiveness (e.g., Dalgaard et al. 2014; Ribaudo 2017). A conceptual problem is the quantification of the environmental costs caused by the diffuse pollution. The knowledge of these costs is required to determine the range of taxes and quotas to design effective and efficient policy instruments (Shortle and Horan 2017).

The controversial discussion in the literature makes it challenging for policy advisors to evaluate the pros and cons of both options. The WBAE (German Scientific Advisory Board on Agricultural Policy, Food and Consumer Health Protection) and the WBW (German Scientific Advisory Board on Forest Policy) discuss the nitrogen tax and the "extensification of production" in their report, "Climate protection in agriculture and forestry and downstream sectors: food and wood" (WBAE and WBW 2016). The two boards find that set-aside, as a potential policy option to reduce agricultural greenhouse gas emissions, can be considered as an extreme expression of the extensification of production. The WBAE and WBW (2016) do not provide a quantification of the effectiveness and the efficiency of either the nitrogen tax or extensification. Nevertheless, WBAE and WBW (2016) consider the application of a tax to mineral nitrogen fertilizer to increase the efficiency in use of nitrogen fertilization and thus to reduce nitrogen input and the associated emission of  $N_2O$ . The WBAE and WBW (2016) do not advise an extensification of agricultural production because the expected development in global agricultural markets could increase demand for food, fibres and energy. The increased demand would require an intensification of farm management if agricultural land retains the same extensions as are currently used for production. An extensification by reducing land would increase the intensification of the farm management; an extensification of farm management would reduce the productivity of land and thus increase the demand for land. Thus, the development of global markets are

important for the evaluation of tools to evaluate extensification, like set-aside, as a policy option.

The study combines three applied policy simulation models for the policy analysis. It aims at contributing to the controversial discussion by analyzing the abatement policies nitrogen tax and set-aside for the case study country Germany. The study aims at providing information on the performance (the effectiveness and efficiency) of these instruments under global economic changes and under changes of agricultural markets. Furthermore, the study presents a top-down linked model framework representing the global, national and regional scale.

## 2 Literature Review

### 2.1 Studies on Agricultural Greenhouse Gas Abatement Options

Several recent studies analyze the impacts, the effectiveness and the efficiency of agricultural GHG abatement options in different European countries or regions. Most of the studies analyze the aspect of abatement measures and policy instruments with different foci.

Agricultural GHG abatement measures can be roughly divided into intensity-based abatement measures and land-use based abatement measures. Intensity based abatement measures directly reduce agricultural GHG emissions by lowering the intensity of farm management. The intensity-based abatement measures particularly reduce the agricultural GHG sources by lowering inputs (e.g., adaptation of fertilization) or reducing the intensity of management processes (e.g., adopting reduced or zero tillage systems). Studies on intensity-based abatement measures often analyze the costs and the applicability of the measures. Thus, such studies focus specifically on the costs of the production-specific processes. However, they do not necessarily evaluate the potential impacts on other production processes.

Zandersen et al. (2016) analyse the effectiveness and efficiency of reduced tillage as an abatement measure to increase the net effects of carbon sequestration in agricultural soils. Albiac et al. (2017) analyse the adjustment of fertilization practices, and the modernization of irrigation techniques and manure management systems in Spain. Dace et al. (2015) analyse the improvement of in-animal digestion to reduce emissions from enteric fermentation (anaerobic digestion management systems (ADMS) and the improvement of manure management systems in Latvia.

For Germany, Osterburg et al. (2009, 2013) evaluate the abatement measures applicable for agricultural production. In addition to the measures analyzed by the other studies, the authors also analyze the effectiveness of an increase in dairy cow productivity, adaptation of herd and pasture management, and the extensification by conversion to organic farming. The authors identify the efficiency increases in fertilization management, the reduction of nitrogen surpluses, the reduction of agricultural production (extensification) and the restoration of peatlands as effective measures for Germany.

Land-use based mitigation measures reduce agricultural GHG emissions by changing the usage of agricultural land. The land-use change can, like intensity-based measures, reduce GHG emissions by a reduction of production intensity (e.g., to convert arable land into set-aside land) and create CO<sub>2</sub> sinks. Instead of being reconverted into arable land, the set-aside area can be converted into grassland or into areas to plant trees as CO<sub>2</sub> sinks, e.g., for short rotation coppices or afforestation.

Studies on intensity-based abatement measures often focus on the abatement potential and costs of the measures. However, in analyzing land-use changes, they automatically consider the potential impacts and changes on other production processes.

For Germany, Krimly et al. (2016) estimate the abatement potential and abatement costs of different peatland management options in southern Germany and compute abatement costs ranging from 5 to 92 EUR/tCO<sub>2</sub>e. Röder et al. (2015) combine the measures “peatland restoration,” “production of short rotation coppices,” and the “production of agricultural biomass (as sink),” and compare them with respect to their effectiveness and efficiency. Röder et al. (2015) show that with restoration of peatlands for costs of 50 EUR/tCO<sub>2</sub>e, a potential of 25 M t CO<sub>2</sub>e can be abated.

Agricultural mitigation policy instruments provide an incentive for the agricultural producer to apply GHG abatement measures. Studies which analyze policy instruments consider—at least implicitly—the abatement measures to be applied. As environmental policy instruments, the agricultural abatement policy instruments can roughly be differentiated into market-based instruments and command and control -instruments.

Market-based instruments (MBI) provide an economic incentive for the producer to reduce GHG emissions (e.g., taxes, subsidies or emission trading). Thus, a correctly designed and implemented market based instrument can be an economically adequate policy instrument. For example, Cara et al. (2018) and Cara and Jayet (2011) focus on the analysis of cap-and-trade and the exemption of monitoring, reporting, and verification costs for small firms in the European member states. Albiac et al. (2017) analyse the application of an emission tax and a tax on the inputs of nitrogen and water in Spain. Dace et al. (2015) simulate a subsidy for renewable energy crops in Latvia as a policy instrument.

For Germany, Neufeldt and Schäfer (2008) simulate a nitrogen tax and compute an abatement cost of 280EUR/tCO<sub>2</sub>e. However, the results are representative for farm types in the southern German region Baden-Wuerttemberg and not for all of Germany. Henseler et al. (2015) simulate a nitrogen tax for whole Germany to illustrate the different regional impacts on N<sub>2</sub>O emissions. However, that study does not focus on the effectiveness or the efficiency of the nitrogen tax.

Command and control policy instruments force the producer to reduce GHG emissions by applying GHG abatement measures in regulative frameworks. Van Doorslaer et al. (2015) and Pérez Domínguez et al. (2016) analyze both market-based instruments in the form of subsidies for the application of abatement technologies, and command and control instruments as an emissions cap-without-trade option for the EU member states.

For the Southern German region of Baden-Wuerttemberg, Neufeldt and Schäfer (2008) simulate an emission cap and a compulsory livestock extensification for typical farming systems and compute abatement costs of 115 EUR/tCO<sub>2</sub>e.

Most of the existing studies analyze the abatement policy options assuming an unchanged global environment. Thus, recent analyses of abatement options do not consider potential changes of the global settings, which could influence the effectiveness and efficiency of the analyzed mitigation strategies.

## 2.2 Integrated Economic Model Frameworks

Many studies use agro-economic models as analytical framework to simulate abatement options at the national scale (e.g., Van Doorslaer et al. 2015; Pérez Domínguez et al. 2016), regional scale (e.g., Röder et al. 2015; Henseler et al. 2015) or at the farm scale (e.g., Krimly et al. 2016; Neufeldt and Schäfer 2008). Agro-economic programming models

apply as stand-alone models, and have generally been accepted as an appropriate method for agro-environmental policy analysis.

Many economic research fields develop and apply integrated economic frameworks to analyze the impact of policy reforms at different economic scales. The two model types often linked to an integrated framework, are computable general equilibrium models (CGE) and partial equilibrium (PE) models. CGE models represent the macro-economic scale with its feedback effects between sectors and the considered regions. PE models can represent the sector scale and the regional, individual producer or household scales. PE models at sector scale allow for detailed representation of policies and sectors (Narayanan et al. 2010; Kretschmer and Peterson 2010) and can represent the economic impact of policies under consideration of social, geographic and biophysical conditions (Kretschmer and Peterson 2010).

Many studies employ CGE and PE models to complementarily use the advantages of both models for multi-scale analysis. CGE models represent the whole economy and provide information on economic shocks by consistently considering all economic sectors. However, based on macro-economic data CGE models provide the results as relative changes of monetary values. The PE models represent the economy partially and specialized on selected sectors. The data base for the sectors in PE models are sufficiently detailed to allow for spatial and commodity disaggregation. Thus, PE models can provide the results in physical quantities, which can be linked easier to environmental indicators (Pelikan et al. 2015; Britz and Hertel 2011).

Some studies analyze complementarily the results of the stand-alone models without linking the models (e.g., Figus et al. 2018; Verikios 2009; Costantini et al. 2013). Other studies link the CGE and PE models to downscale from the macro-economic scale to the specific sectoral or to the regional/individual producer or household, or upscale from the producer/household scale to the macro-economic scale (e.g., Pelikan et al. 2015; Henseler et al. 2013; Debowicz and Golan 2014).

The linkage between CGE models and PE models at producers/households scale is established as the macro–micro linking approach. The CGE model represents the macro-economic level with representative types of households and producers. The micro economic PE model represents the producers/households level with differentiated types of households or producers. The macro–micro linkage often addresses analysis of policies with direct impact on the households' income or wealth (e.g., fiscal policies) (see Labandeira et al. 2009; Roe et al. 2005; de Quatrebarbes et al. 2016).

The linkage between a CGE model and a PE model at the sector scale is less represented in economic literature. This linkage analyzes the impact of policy instruments at both the macro-economic level and sector level (e.g., trade, transport, energy) and often addresses sector-specific policy instruments such as trade policies and energy policies (e.g., Calzadilla et al. 2013; Britz and Hertel 2011; Henseler et al. 2013, Pelikan et al. 2015).

The linking between models of all three scales—a CGE model, a PE model at sector scale and a PE model at regional producer/household—is under-represented in the economic literature. The linking of three different models types requires the model expertise of each model, the capacities to link the models and the ability to interpret the results consistently. Thus, linking the three models is costly, and researchers often define their research questions/problem so that they can be sufficiently addressed by using only one model or a maximum of two models. However, some research questions benefit from or even require the consideration of three model scales: macro-economic, the sectoral and the actor's level.

Addressing our research question requires the three level down-scaling in order to consistently represent the impacts from global change scenarios (at the global economy) on the

global agricultural markets (at the European/national scale), which can then be considered for the simulation of mitigation options at the regional producers' scale.

Table 1 provides an overview of selected economic studies in different research fields. The studies apply a CGE model and a PE model to address specific research questions by either analyzing the results complementarily or linking them as integrated models.

Our study complements the literature with a policy analysis of two mitigation instruments based on three applied policy simulation models. The models represent three spatial and economic scales: the global economy, global agricultural markets and regional agricultural producers. The linked models have been developed for their specific research domains and they have been applied in several studies as stand-alone models or in model frameworks. Our study presents the first policy analysis based on the combination of the three models: DART (Dynamic Applied Regional Trade)-BIO, CAPRI (Common Agricultural Policy Regionalised Impact) model and RAUMIS (Regional Agricultural and Environmental Information System) model.

### 3 The Integrated Model

#### 3.1 The Model Framework

The assessment of the regional impacts of a policy instrument under global change scenarios requires (at least) a two-dimensional downscaling: the regional downscaling and the sectoral downscaling (Fig. 1, left hand side). To capture this challenge, we link three different economic models to an integrated top-down model. The CGE model DART-BIO simulates the world economy at the global scale. The PE model CAPRI simulates the agricultural markets at the national scale and the regional supply model RAUMIS simulates the producers at the regional scale.

We link the models top-downwards while transmitting the information of the changes of the economic key drivers (i.e., the shock) from the global economy to regional agricultural production, without calibrating the models to each other. This “soft linkage” (Britz 2008) allows the models to respond to the economic shocks without being constrained by the calibration to the other models.

The three models have been extensively validated in many different scientific applications for the reliability of their reactions and results on their respective scales and for their sectors (see Table 2). In the present study, we couple these models by a “soft linkage” (Britz 2008). We believe that based on their validated stand-alone reactions, the model results are more suitable than calibrating the models to each other. A calibrated linkage could cause problems because reaching a consistent calibration between three models might reduce the freedom of the models to react according to their expertise. The expert calibration will be influenced by the calibration of the other models.

Figure 1 presents the downscaling and information transfer within the integrated model. The CGE model DART-BIO simulates global economic scenarios based on values for 23 world regions for the period from 2007 to 2030. It provides the information on the impacts on the indicators energy prices, agricultural world market prices and Gross Domestic Product (GDP). The change in the GDP represents the general economic situation, while energy prices and agricultural world market prices are key drivers for the European agricultural markets. Thus, the DART-BIO model transfers these relative changes as information of global economic scenarios to the PE model CAPRI.



**Table 1** Selected studies of different research fields which apply CGE and PE models to analyze policy instruments at different levels

Research field	Research question	Simulation scales		Study
		Macro economic level: CGE model	Sectoral level: PE market model (supply demand)	
Energy policy	Distributional analysis of energy policies' efficiency and equity in energy tax reforms in Spain	Static CGE model of the Spanish economy	Regional/individual producer/household level: PE micro model (supply or household model)	Labandeira et al. (2009)
Transportation	Efficiency of the vehicle input in the household production of private transport in UK	UK-ENV1 <sup>a</sup>	Household production of private transport <sup>a</sup>	Figus et al. (2018)
Trade policy—water sector	Impact on trade reforms on water productivity in Morocco	Two-sector CGE model	Micro model farm supply farm actors	Roe et al. (2005)
Trade policy—textile sector	Impact of wool tariff barriers on world wool market	CGE model of world regions <sup>a</sup>	Comparative static PE of the wool sector <sup>a</sup>	Verikios (2009)
Trade policies—agricultural sector	Impacts of trade disruption of EU soy imports	GTAP-AGR	ESIM for European agricultural markets	Henseler et al. (2013)
Poverty policy—household income	Distributional effects of cash transfer program on poverty and income distribution in Mexico	IFPRI Standard CGE Model	Micro simulation model	Debowicz and Golan (2014)
Fiscal policies—poverty and income distribution	Distributional analysis of fiscal policies on poverty and income distribution in Niger	Static CGE model	Microeconomic model for household income	de Quatrebarbes et al. (2016)

**Table 1** (continued)

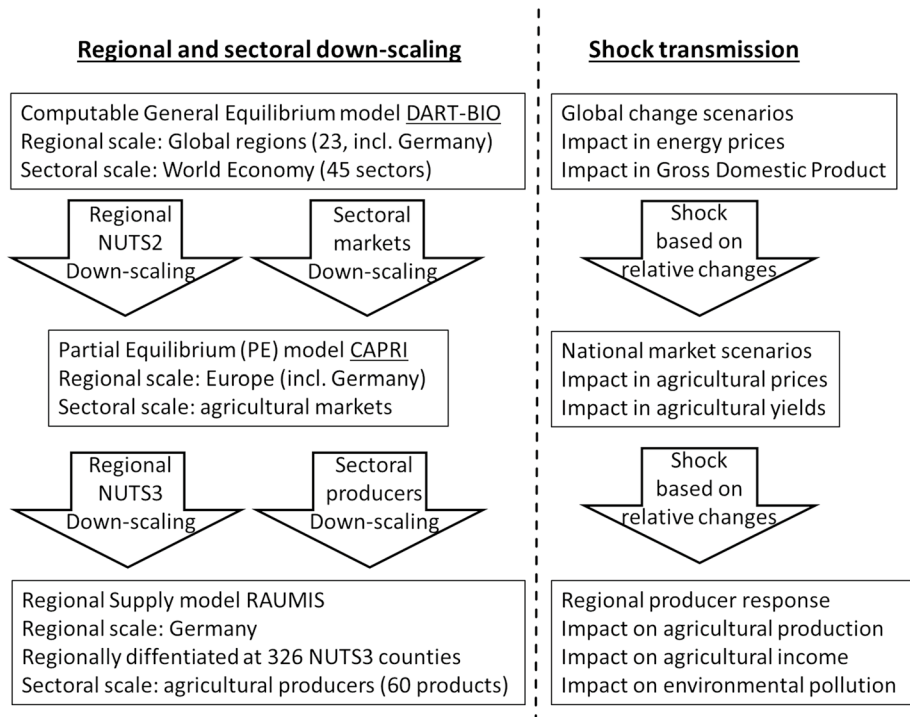
Research field	Research question	Simulation scales		Study
		Macro economic level: CGE model	Sectoral level: PE market model (supply demand)	
Mitigation policies	Efficiency, effectiveness and impacts of emission trading and taxation as mitigation policy	GTAP-E <sup>a</sup>	Theoretical stylized PE model <sup>a</sup>	Costantini et al. (2013)
Climate change impact—adaptation measures	Impact of climate change and irrigation on agricultural production in world regions	GTAP-W	IMPACT	Calzadilla et al. (2013)
Mitigation policies	The impact of international emissions trading as mitigation policy instrument	EPPA model <sup>a</sup>	Partial equilibrium model based MAC <sup>a,b</sup>	Webster et al. (2010)
Trade policies (biofuel policies)—environmental quality	The impacts of EU biofuels policies on land use and nutrient surplus as indicator for environmental quality	GTAP	CAPRI	Britz and Hertel (2011)
Environmental policy, extensification policy	Impact of biodiversity-targeted ecological focus area (EFA) on all farms in EU	GTAP-AEZ	CAPRI-FT	Pelikan et al. (2015)

**Table 1** (continued)

Research field	Research question	Simulation scales		Study
		Macro economic level: CGE model	Sectoral level: PE market model (supply demand)	
Mitigation policy	Regional Impacts of Greenhouse Gas Abate- ment Policy Instruments under Global Change: a Modeling Study for agricultural production in Germany	DART-BIO	CAPRI	RAUMIS  Present study

<sup>a</sup>No direct linkage between the models only complementary analysis of results

<sup>b</sup>MAC marginal abatement curve



**Fig. 1** Overview of both aspects of model linkage: the down-scaling (left) and the shock transmission (right)

The PE model CAPRI simulates the impacts of global change on the global agricultural market differentiated for the European agricultural markets. The CAPRI model database consists of statistical data of production quantities, area, prices and yields and simulates the absolute changes of these variables. Based on absolute values for agricultural production data, the CAPRI model is linked to the regional supply model RAUMIS.

The regional supply model RAUMIS bases on statistical data of production quantities, area and yields and provides changes resulting from the impact of global change scenarios and the impact of policy instruments. The supply model results allow for the analysis of impacts on agricultural production, environment and income and the evaluation effectiveness and efficiency of the simulated policy instruments.

The applied top-down model linkage considers only the transfer of the shock from the global scale via the markets to the regional scale. It does not allow the feed-back of the shock from the regional model to the markets or the global model, i.e., bottom-up. Such a bottom-up response requires the calibrated linkage of the three models in both directions of the model chain to ensure consistent reactions. The calibration of such a linkage is very complex and it restricts the reactions of each model. In our study, we apply a soft linkage to the models in top-down direction to address the research questions of interest.

**Table 2** Selected characteristics of the top-down linked models: DART-Bio, CAPRI and RAUMIS

Name	Model approach	Time resolution, calibration	Regional scale	Sectoral scale	Output	Exemplary references of relevant applications
DART-Bio	Multi-regional CGE model	Recursive-dynamic, ex-post	23 world regions	The world economy, 45 economic sectors	Percentage changes of prices volumes and macro-economic indicators	Global change: Delzeit (2018a, b) Delzeit et al. (2018a, b) Delzeit et al. (2017) Calzadilla et al. (2016) Delzeit et al. (2010) Documentation: Calzadilla et al. (2016) Springer (1998)
CAPRI	Multi-regional PE model	Comparative-static, ex-ante	EU member states 19 NUTS2 regions in Germany	25 crop products, 10 animal products, 25 further processed products	Absolute changes of supply and demand quantities, yields and prices	CAP analysis/market policies: Offermann et al. (2016) Pérez Domínguez and Holm-Müller (2008) Gocht et al. (2013) Johansson et al. (2007) Piketty et al. (2009) Trade and environment: Himics et al. (2018) Fellmann et al. (2018) Documentation: Britz and Witzke (2014)

**Table 2** (continued)

Name	Model approach	Time resolution, calibration	Regional scale	Sectoral scale	Output	Exemplary references of relevant applications
RAUMIS	Regional supply model	Comparative-static, ex-post	326 NUTS3 regions in Germany	Agricultural production activities with 32 crops 15 animals	Absolute changes of regionalized environmental indicators	Pesticide application: Sieber et al. (2010) Nitrogen emissions: Gömann et al. (2011) Kunkel et al. (2010) Hirt et al. (2012) Greenhouse gas emissions/mitigation: Röder et al. (2015) Henseler et al. (2015) Documentation: Henrichsmeyer et al. (1996)

### 3.2 The Linked Models

The three models linked in the integrated model framework are scientifically referenced simulation models. They have been applied in various different policy analyses for specific regional and sectoral scales. Table 2 presents the characteristics of the linked models and examples of applications which are relevant for this study.

### 3.3 The DART-BIO Model

The Dynamic Applied Regional Trade (DART) model is a multi-sectoral, multi-regional recursive-dynamic CGE model of the world economy (e.g., Springer 1998). The DART model is based on the Global Trade Analysis Project (GTAP) database covering multiple sectors and regions. DART is based on microeconomic theory: The economy in each region is modelled as a competitive economy with flexible prices and market clearing conditions. A global equilibrium is reached by simultaneously matching the demand and supply for all goods, domestic and foreign, on all markets given by the external determinants, such as population, capital endowments, technologies, tax and trade policies or other policy measures (for example, subsidies or biofuel policies). The model follows a recursive-dynamic approach where it solves for a sequence of static one-period equilibria for future time periods. The transition from one period to the other is governed by capital accumulation, changes in labor supply and technological change.

The present study uses the DART model in the specification DART-BIO. This version of the DART model generates annual data on prices, quantities and trade-flows for 23 regions which are subdivided into 18 so-called agro-ecological zones (AEZs), 38 sectors, which produce 45 commodities<sup>1</sup> and into 21 factors of production. For a more detailed description of the model see Calzadilla et al. (2016). DART simulates the development of GDP and energy price changes for the period 2007–2030 and passes the values of the last year to the CAPRI model. In several studies researchers apply DART to simulate and analyze impacts of global change on agricultural and energy markets (e.g., Delzeit et al. 2018a, b; Calzadilla et al. 2014; Delzeit et al. 2010).

### 3.4 The CAPRI Model

CAPRI (Common Agricultural Policy Regionalised Impact analysis) is a partial equilibrium model that simulates regional European agricultural markets. CAPRI represents the markets' behavioral supply and demand functions and the corresponding equilibrium prices. The supply functions distinguish between area and yield response and let the model react to changes in agricultural prices, in production quantities, in agricultural land demand and land quality. CAPRI is a comparative static model that is calibrated ex-ante based on trend and expert estimates, closely linked to the OECD–FAO Agricultural outlooks. The model features a detailed representation of the agricultural sector in the EU at regional (NUTS2) (district) level. This part is linked to a global market model that represents—in less detail—international agricultural markets and trade flows. Manifold specifications

<sup>1</sup> Some of the 38 sectors produce more than one commodity, e.g., oilseed sectors produce vegetable oil and vegetable meals in a joint production process. Thus, the number of commodities exceeds the number of sectors.

allow researchers to apply CAPRI to various research fields, such as agricultural markets and trade (Piketty et al. 2009), agricultural policies (Johansson et al. 2007), biofuel policies (Blanco et al. 2013), and environmental policies (Fellmann et al. 2018; Himics et al. 2018). Researchers use CAPRI to analyze their topics at different regional scales: EU member states, NUTS2-district scale and EU farm type scales (Gocht et al. 2013). For a more detailed description of CAPRI see Britz and Witzke (2014).

In our study we use CAPRI to simulate the European agricultural markets including agricultural yields and prices for Germany. The model differentiates 25 crop products, ten animal products and 25 further processed products. Via the model linkage CAPRI hands over the relative changes of prices and yields to RAUMIS.

### 3.5 The RAUMIS Model

Complementary to CAPRI, the RAUMIS model (Regionalized Agricultural and Environmental Information System) focusses on the simulation of agricultural producers and emission of environmental pollutants in Germany. As a supply model, RAUMIS considers the heterogeneities of regional production conditions at the high regional resolution of NUTS3 (county) scale. Thus, RAUMIS allows for a specific impact analysis of agricultural and environmental policies on agricultural producers in Germany (Henrichsmeyer et al. 1996).

RAUMIS represents the regional producers' production activities by optimizing a system of regional production functions and a non-linear objective function. The equation system maximizes the agricultural income and considers, regionally specified, the agricultural production processes of crop and animal production. RAUMIS is ex-post calibrated on regional data of agricultural area and husbandry, yields and quantities of input factors (e.g., fertilizer). RAUMIS provides the changes in absolute quantities under scenario simulation for the same variables.

RAUMIS accounts for different environmental pollutants emitted by agricultural production. It computes the emission of pesticides per crop activity based on the sectoral costs for pesticides (Sieber et al. 2010). RAUMIS computes the emission of nutrients (nitrogen, phosphate) resulting from the application of mineral and organic fertilizer. A nutrient balance accounts for the nutrient supply from livestock, for the nutrient demand from crop production and losses to the atmosphere (Gömann et al. 2011). Specific GHG emission models for soil emissions and for livestock provide the data for RAUMIS to compute GHG emissions from crop production animal production and manure management ( $N_2O$ ,  $CH_4$ ,  $CO_2$ ) (Henseler and Dechow 2014; Röder et al. 2015).

RAUMIS differentiates simulation of regional agricultural supply, environmental pollution and agricultural income for 326 counties (NUTS3), 25 crop products at different production intensities, and also ten livestock activities. Numerous research and policy studies use RAUMIS to analyze impacts of environmental policies and to provide an accounting of greenhouse gas emissions (see Table 2).

## 4 The Scenarios and Results

### 4.1 The Global Economic Scenario BAU Scenario (DART-Bio)

The Business as Usual (BAU) scenario is defined to carry forward the present situation until 2030 with current developments and trends, including current legislation on land



use, trade policies, nutritional habits and, specifically, the current global biofuel mandates which are defined until 2020 and assumed to be met from then on. Further, with respect to EU policies, the 2013 CAP reform is implemented making assumptions on ecological set aside, crop diversity and pasture conservation.

With respect to biofuel policies in the baseline scenario, we align our baseline to the assumptions of OECD/FAO (2016) where all the EU regions reach a bioethanol share of 7.8% and a biodiesel share of 8% on total consumption of transport fuels. The national disaggregation for the EU member states, not available from the OECD, are adapted according to the national action plans documentation and the national biofuel targets (Beurskens et al. 2011). We assume that these targets will not change until 2030.

#### **4.2 The Global Economic Lower Price Scenario (LP) (DART-Bio)**

This scenario represents a tendency towards larger agricultural supply and less demand according to Delzeit et al. (2018a, b). On the one hand, the authors assume that the abolishment of biofuel quotas causes less demand for crops. On the other hand, cropland expansion and higher yields resulting from partial closing of regional yield gaps cause a higher production of crops.

Particular production increases are simulated for palm fruit and ‘other oil seeds’ in global regions with a large potential of land expansion and yield increase (e.g., Malaysia/Indonesia, Sub-Saharan Africa, Latin America). The global agricultural markets react to the decreased crop demand and to the increased crop supply by a decrease in global agricultural prices (Delzeit et al. 2018a, b).

The cropland expansion is based on the FAO long-term baseline outlook (Alexandratos and Bruinsma 2012). Details on the calculation of additional land endowment as well as a detailed discussion of results are available in Delzeit et al. (2017). The agricultural productivity is implemented by an assumption on a partial closing of regional yield gaps. Specifically, the regional yield gap ratio, which is the potential agro-economic yield divided by the statistical yield, is reduced by 5%. The approach of simulating yield gap ratios is described in Mauser et al. (2015). A detailed description of the Lower-price scenario is available in Delzeit et al. (2018a, b).

#### **4.3 The Global Economic Higher Price Scenario (HP) (DART-Bio)**

With this scenario the combined effect of multiple supply and demand drivers on current agricultural land leading to a high pressure on current cropland in use is assessed, i.e., a high demand for production area. Under this scenario (taken from and described in detail in Delzeit et al. 2018a, b). The scenario considers biofuel policies and the other policies as the BAU scenario. In addition, it is assumed that there is no expansion of agricultural land. A higher preference in Asian regions for meat and dairy products increases global agricultural prices. At the same time, a lower productivity growth in the agricultural sector is implemented by having yield increases 0.2 percentage points less than in the BAU. Assuming a lower productivity growth prevents high increases in global production intensities and supply, which could be expected as result of the increased prices. Even the production of the main feedstocks as a base for meat and dairy production does not increase relative to the BAU scenario, despite a shift of land towards these crops. Thus, the assumption of lower productivity growths results in a high price increase under retained high area demand.

**Table 3** Change in prices of energy products, and change in Gross Domestic Product in Germany for the higher price and lower price scenarios compared to the baseline scenario in 2030

	Higher price scenario		Lower price scenario	
	Global average	Germany	Global average	Germany
<i>% change compared to business as usual</i>				
Crude oil price	-0.1	-0.1	1.2	1.0
Transport diesel	-0.1	-0.1	1.2	1.1
Transport gasoline	-0.1	-0.1	1.2	1.1
Gross Domestic Product	-0.1	0	1.0	0.1

Crops prices increase most in the EU, Africa and Middle East due to relatively higher productivity. Though the demand for meat and dairy products has increased a lot in Asian regions, the increase in crop prices in Asian regions is relatively small, resulting from lower productivity increases in Asian regions, and decreases less than in other global regions (Delzeit et al. (2018a, b)).

#### 4.4 Impacts of the Global Scenarios on the German and World Economy

Global energy prices increase by 1.2% until 2030 in the Lower-prices scenario, mainly caused by the abolishment of biofuel policies. Energy prices in Germany increase by up to 1% compared to the Baseline Scenario. The Higher-price scenario does not significantly affect energy prices (Table 3). Increases in agricultural yields cause increase in agricultural value-added, but since the agricultural sector has a very small share in total Gross Domestic Product (GDP) in Germany, both scenarios have only a very limited impact on the total German GDP. Changes in energy prices and GDP generated with the DART model for all 23 world regions are passed on to the CAPRI model.

#### 4.5 Impacts of the Higher Price Scenario on German Agricultural Markets (CAPRI-RAUMIS)

The high world demand for agricultural commodities and the high global demand for land increase the prices on the German agricultural markets, particularly for cereals, oilseeds, dairy, pork and poultry (Table 4). Despite the general decreasing yield trend for most of the commodities, the German cereal and dairy sector react to the high global demand with slightly increased yields/productivity. Hence, the exogenously assumed low increases in productivity are overcompensated by endogenously simulated increases in German yields because of higher crop prices.

German farmers maximize their income by extending the production of the profitable high priced cereals (+1%). The farmers increase the production intensity and extend the cereals area by reducing area for fodder (-2%), energy maize (-1%) and set-aside (-6%). Increasing prices for dairy, meat and the intensification of crop production allow farmers to increase their income (+5%). However, the intensification in cash crop production (e.g., wheat and oilseeds) results in increased environmental pressure by increased pesticide usage (+0.3%), nitrogen balance (+0.6) and GHG emission (+2%).

**Table 4** Impact of global scenarios on prices and yields of products on German agricultural markets in percent compared to the BAU (= 100) (results from CAPRI) and on agricultural producers (results from RAUMIS)

	CAPRI				RAUMIS		
	Higher price scenario		Lower price scenario		Business as usual	Higher price scenario	Lower price scenario
	Price	Yield	Price	Yield			
	%	%	%	%	Absolute value (a)	%	%
<i>Production</i>							
Wheat	1.9	0.0	-3.0	-1.2	3.27 <sup>a</sup>	0.7	0.6
Barley	2.0	1.5	-3.1	0.0	1.13 <sup>a</sup>	2.1	2.1
Other cereals	2.2	0.0	-4.0	-1.8	1.55 <sup>a</sup>	0.3	-0.5
Oilseed	2.6	0.0	-20.3	0.0	2.16 <sup>a</sup>	0.4	-0.9
Root crops	0.9	-0.7	-0.3	0.0	0.69 <sup>a</sup>	0.1	-4.6
Other cash crops	1.8	0.0	0.1	3.8	0.38 <sup>a</sup>	0.0	0.0
Arable fodder	NA	NA	NA	NA	1.77 <sup>a</sup>	-1.9	-0.5
Intensive grassland	NA	NA	NA	NA	2.53 <sup>a</sup>	0.0	0.0
Extensive grassland	NA	NA	NA	NA	1.77 <sup>a</sup>	0.0	0.0
Fallow	NA	NA	NA	NA	0.38 <sup>a</sup>	-6.6	3.7
Energy maize	NA	NA	NA	NA	0.86 <sup>a</sup>	-1.0	0.9
Dairy	1.6	0.0	0.0	-1.4	4.15 <sup>b</sup>	0.0	0.2
Other cattle	1.6	0.0	0.3	0.0	4.19 <sup>b</sup>	0.0	0.2
Pork	1.8	0.8	0.5	8.2	2.82 <sup>b</sup>	0.0	0.0
Poultry	1.7	0.0	-0.1	0.0	0.50 <sup>b</sup>	0.0	0.0
Other animals	0.0	0.0	0.0	0.0	0.79 <sup>b</sup>	0.0	0.0
<i>Environment</i>							
Pesticide costs	NA	NA	NA	NA	1784.15 <sup>c</sup>	0.3	-0.3
Nitrogen balance	NA	NA	NA	NA	0.81 <sup>d</sup>	0.6	-0.3
CO <sub>2</sub> emissions	NA	NA	NA	NA	79 <sup>e</sup>	81	81
Mitigation	NA	NA	NA	NA	79.17 <sup>e</sup>	2.4	1.8
<i>Income</i>							
Income	NA	NA	NA	NA	25,737 <sup>f</sup>	4.7	-3.0

<sup>a</sup>Million ha; <sup>b</sup>Million LU; <sup>c</sup>pesticide costs in Million EUR; <sup>d</sup>nitrogen balance in Million t N; <sup>e</sup>CO<sub>2</sub> emissions and mitigation in Million t CO<sub>2</sub>e; <sup>f</sup>income in Million EUR

#### 4.6 Impacts of the Lower Price Scenario on German Agricultural Markets (CAPRI-RAUMIS)

The lower world demand for agricultural commodities and the high supply decreases the prices for all commodities on the German agricultural markets. Particularly the oilseed prices reduce because of the abolishment of biofuel quotas and the resulting decrease in demand for biofuels and because of the increase in production of palm fruit and other oil seeds in global regions (e.g., Malaysia/Indonesia, Sub-Saharan Africa, Latin America) (Delzeit et al. (2018a, b)).

The German agricultural sector reacts to the low demand with decreased productivity. Only the pork sector, which is in Germany extremely competitive, retains its competitiveness. The decreased fodder prices (e.g., wheat, barley) allow intensive fattening and increased productivity in pork production.

German farmers maximize their income by extending the production cereals (+1%), energy maize (+1%), and dairy (+0.2%). However, the low agricultural prices and yields significantly reduce the competitiveness of agricultural production. Thus, farmers reduce production intensity and extension by fallow (+4%). Low fodder prices reduce the feeding costs and allow an increase in dairy cows (+0.2%) and feeding cattle (+0.2%).

Overall the reduction in production intensity and cropland expansion decreases farm income (−3%). The environmental pressure reduces only partially for pollution caused by crop production. Pesticide usage and nitrogen balance decreases (−0.3%). The GHG emissions increase because of the increase in GHG emissions from increasing cattle stocks (digestive emissions). An interesting impact of the Lower Price scenario is an increase in energy maize production. While biofuel policies are abolished in this scenario, the production of biogas to substitute electricity is in place. Lower demand for food and biofuels causes the use of maize for electricity production to rise.

#### 4.7 Impacts of the Environmental Policies on German Agricultural Production (RAUMIS)

The global changes in DART-BIO drive the CAPRI model, which provides the changes of agricultural yields and prices on German agricultural markets. CAPRI transfers the changes of prices and yields to RAUMIS to simulate the impacts of the global change on German regional agricultural producers: i.e., regional agricultural production, income and environmental impacts.

We simulate the environmental policies of nitrogen tax and obligatory set-aside at different levels for the two global scenarios and we compare their impacts with the corresponding global scenarios without implemented policy. The development of selected indicators quantifies the impacts on agricultural production (e.g., development of crop production) and agricultural income (i.e., the net income) and environment (e.g., the nitrogen balance). We select the levels of policy instruments with comparable abatement effect of 4–5% and 9–10% reduction of mitigation of GHG emissions. Furthermore, we analyse the ecological effectiveness and the economic efficiency (cf. Endres 2013; Perman et al. 2011) and quantify the ecological effectiveness by the GHG abatement effect achieved. To analyze the economic efficiency we compute the average abatement costs, based on the abatement effect achieved and the losses in net-income.

##### 4.7.1 Impact at Sector Level

In the Higher Price Scenario under nitrogen tax regime, the farmers adapt their production according to the increased prices for mineral fertilizer. They reduce the production intensity and the production area of cereals, other cash crops and energy maize and (mainly intensive) grassland (see Table 5). They partially substitute decreased supply of roughage from grassland by an increased production of arable fodder. Thus, the farmers increase slightly the level of animal stock (dairy cows and pigs) and thus the production of highly priced animal products (milk and meat). The increased livestock level allows an increased production of manure. Farmers use manure to substitute partially the taxed mineral fertilizer

**Table 5** Impact of policy measures on German agricultural production, income and environment in different global scenarios compared to the corresponding global scenario baseline

	Higher prices				Lower prices			
	Nitrogen tax +40%	Nitrogen tax +80%	Set-aside 15% UAA	Set-aside 25% UAA	Nitrogen tax +10%	Nitrogen tax +40%	Set-aside 15% UAA	Set-aside 25% UAA
<i>Production</i>								
Wheat <sup>a</sup>	-0.171	-0.494	-0.431	-0.915	-0.171	-0.493	-0.431	-0.915
Barley <sup>a</sup>	-0.029	-0.113	-0.297	-0.706	-0.029	-0.113	-0.297	-0.706
Other cereals <sup>a</sup>	-0.067	-0.194	-0.263	-0.622	-0.066	-0.193	-0.261	-0.617
Oilseed <sup>a</sup>	-0.119	-0.369	-0.373	-0.876	-0.118	-0.364	-0.368	-0.865
Root crops <sup>a</sup>	-0.001	-0.005	-0.014	-0.026	-0.001	-0.005	-0.013	-0.025
Other cash crops <sup>a</sup>	-0.023	-0.023	-0.030	-0.034	-0.023	-0.023	-0.030	-0.034
Arable fodder <sup>a</sup>	0.071	0.198	-0.109	-0.219	0.072	0.201	-0.111	-0.222
Intensive grassland <sup>a</sup>	-0.089	-0.149	-0.311	-0.536	-0.089	-0.149	-0.311	-0.536
Extensive grassland <sup>a</sup>	-0.044	-0.074	-0.303	-0.554	-0.044	-0.074	-0.303	-0.554
Set-aside <sup>a</sup>	0.205	0.268	0.304	0.324	0.228	0.298	0.338	0.360
Energy maize <sup>a</sup>	-0.042	-0.069	-0.438	-0.865	-0.043	-0.070	-0.446	-0.882
Dairy <sup>b</sup>	0.025	0.000	-0.237	-0.473	0.025	0.000	-0.237	-0.474
Other cattle <sup>b</sup>	0.025	-0.021	-0.247	-0.469	0.025	-0.021	-0.248	-0.470
Porks <sup>b</sup>	0.034	0.051	-0.003	-0.003	0.034	0.051	-0.003	-0.003
Poultry <sup>b</sup>	0.002	0.003	0.000	-0.001	0.002	0.003	0.000	-0.001
Other animals <sup>b</sup>	0.002	0.002	-0.012	-0.028	0.002	0.002	-0.012	-0.028
<i>Environment</i>								
Pesticide costs <sup>c</sup>	-50	-122	-165	-295	-50	-121	-164	-294
Nitrogen balance <sup>d</sup>	-0.02	-0.06	-0.08	-0.14	-0.02	-0.06	-0.08	-0.14
CO <sub>2</sub> emissions <sup>e</sup>	78	73	77	73	77	73	77	73
Mitigation <sup>e</sup>	-3	-8	-4	-8	-3	-8	-4	-8

**Table 5** (continued)

	Higher prices			Lower prices		
	Nitrogen tax +40%	Nitrogen tax +80%	Set-aside 15% UAA	Nitrogen tax +10%	Nitrogen tax +40%	Set-aside 25% UAA
<i>Income</i>						
Net value added at factor cost <sup>f</sup>	-781	-2506	-1509	-724	-2322	-2696

<sup>a</sup>Million ha; <sup>b</sup>Million LU, million t CO<sub>2</sub>e, Million EUR; <sup>c</sup>pesticide costs in Million EUR; <sup>d</sup>Nitrogen balance in Million t N; <sup>e</sup>CO<sub>2</sub> emissions and mitigation in Million t CO<sub>2</sub>e, Mitigation in Million t CO<sub>2</sub>e; <sup>f</sup>income in Million EUR

and thus compensate the increasing production costs. Set-aside area increases and indicates a net-decrease in agricultural production, which reduces the environmental impacts and the agricultural income in comparison to the Higher Price Scenario without implemented nitrogen tax.

Under a compulsory set-aside regime, the farmers increase the set-aside area until fulfilling the prescribed quota and reduce all crop and animal production activities. The set-aside obligation reduces the production land used for agricultural production and the related environmental pollution from pesticides and nitrogen. However, the consequent shortage of agricultural land significantly reduces farmers' flexibility to compensate losses in production, e.g., by reallocating land from less profitable to more profitable activities. Thus, farmers lose significantly in income.

To meet the same abatement targets in the Lower Price Scenario the level of nitrogen tax is smaller (+10% and +40%) than in the Higher Price Scenario (+40 and +70%). The changes in agricultural production are comparable to the reactions in the Higher Price Scenario. Only the set-aside area tends to increase slightly more. However, the lower agricultural prices and yields require a smaller price shock on the production factor nitrogen (i.e., the nitrogen tax) than in the High Price scenario.

The lower agricultural prices and yields decrease the profitability of all production activities and make the agricultural production sector more vulnerable for increase of factor prices. Farmers already react to a relatively small increase of the nitrogen price by adapting their production towards a more efficient allocation of nitrogen. The obligatory set-aside area results in both scenarios in comparable impacts on production, environmental impacts and income for the corresponding mitigation levels.

The command and control instrument of obligatory set-aside appears to be the instrument with a better ecological effectiveness. In both scenarios the same set-aside quota results in comparable impacts on production, environment and income. Thus, policy makers are more informed on expected incomes and how the agricultural sector might react. The level of nitrogen tax requires an adaptation to the corresponding price situation. However, as a market based policy instrument, the nitrogen tax allows farmers to adapt their production according to the increased prices for nitrogen with more flexibility than the quota instrument. Farmers adapt the production intensity and extension of production, increase the efficiency of fertilization of organic nitrogen and thus reallocate their production factors toward higher economic efficiency. Thus, the farmers suffer less income losses from the nitrogen tax than from the compulsory set-aside. Furthermore, the nitrogen tax directly targets one source provoking N<sub>2</sub>O emissions. Thus, this policy directly targets the source of pollution, contrary to the set-aside obligation, which only indirectly reduces the sources of GHG emission by shortage of land.

#### 4.7.2 Ecological Effectiveness and Economic Efficiency

To compare the ecological effectiveness and economic efficiency of the policy instruments we compute the average abatement cost and plot them as abatement cost curve in relation to their effective GHG abatement (Fig. 2).

In both global scenarios the abatement cost curves for the obligatory set-aside quota are between 400 and 600 EUR/t CO<sub>2</sub>e and are significantly higher than for the nitrogen tax with 150–300 EUR/t CO<sub>2</sub>e. Thus, the nitrogen tax seems to be more efficient than the obligatory set-aside. The higher efficiency results from a higher flexibility of farmers to react with production adaptation and the direct targeting of nitrogen as a pollutant.

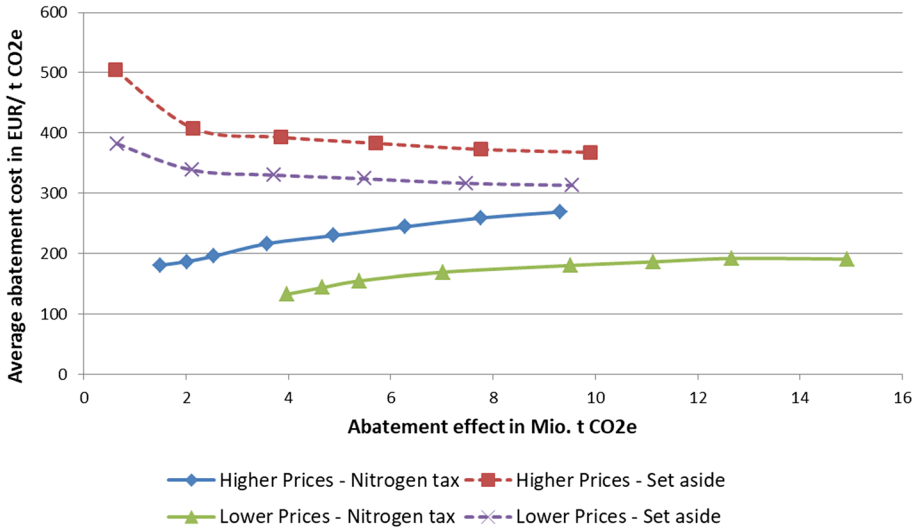


Fig. 2 Marginal abatement cost curves of the policy instruments under the global scenarios compared to the corresponding baseline scenario in 2030

Unsurprisingly, the abatement costs in the Higher Price scenarios are larger than in the Lower Price Scenarios due to increased prices and decreased yields.

### 4.7.3 Nitrogen Tax

The level of the nitrogen tax varies from +20 to +80% increase of nitrogen fertilizer price. The abatement of GHG emission reaches from 2 Mio t CO<sub>2</sub>e to a maximum of around 9–10 M t CO<sub>2</sub>e. The concave abatement cost curve results from farmers' adaptation of production. As a reaction to the increased costs of nitrogen fertilizer, farmers re-allocate the production factors (land, fertilizer) to the more profitable activities, by reducing production intensity (i.e., fertilization), and by increasing efficiency of fertilization with manure. With higher abatement, the possibilities of adaptation also reduce due to the substitution of mineral fertilizer by organic fertilizer. The availability of nitrogen from manure depends on the number of animals, and feeding these animals depends on intensive fodder production. Intensive fodder crop production partially requires the fertilization with the taxed mineral fertilizer. The reduced flexibility the adaptation makes it more expensive per additional unit of abated CO<sub>2</sub>e. Thus, farmers abate CO<sub>2</sub> with a marginally decreasing rate.<sup>2</sup>

The farmers adjust their production in a nearly linear way and can extend the Lower Price scenario to a very high abatement effect of more than 14 M t CO<sub>2</sub>e. At this part of the curve, the average abatement costs remain constantly at 200 EUR/t CO<sub>2</sub>e. However, the high level of abatement of 15 M t CO<sub>2</sub>e results into high total income losses of 12%.

<sup>2</sup> In RAUMIS (as a PE supply model), the reaction of the agricultural markets is not modelled. Thus, RAUMIS does not consider the changes of prices and yields for agricultural commodities resulting from the policy instruments.



For nitrogen tax we simulate abatement costs between 150 and 300 EUR/t CO<sub>2</sub>e. This range is comparable to the abatement costs computed by Neufeldt and Schäfer (2008) and Albiac et al. (2017) with 280 and 310 EUR/t CO<sub>2</sub>e. The impact of a nitrogen tax on agricultural income (and thus on the abatement cost) depends directly on the level of the agricultural commodity prices. Thus, the smaller lower bound of our results with less than 200 EUR/t CO<sub>2</sub>e can be explained by the low prices assumed in the Lower Price Scenario. Thus, the comparison with other studies contributes to the validation of our results.

#### 4.7.4 Obligatory Set-Aside

The levels of obligatory set-aside quota vary from a minimum share of 10% of the Utilized Agricultural Area (UAA) to 30%. The abatement of GHG emission reaches from 2 M t CO<sub>2</sub>e to a maximum of around 9–10 M t CO<sub>2</sub>e at the highest level. The curvature of the curves is convex because at a low abatement level (i.e., low set-aside quota), the farmers first stop production on less productive marginal land (e.g., extensive grassland). Marginal land emits less CO<sub>2</sub>e than highly productive land (i.e., intensively farmed land). With increasing level of abatement (i.e., set-aside quota), farmers increase the abandoning of production on productive farm land and livestock.

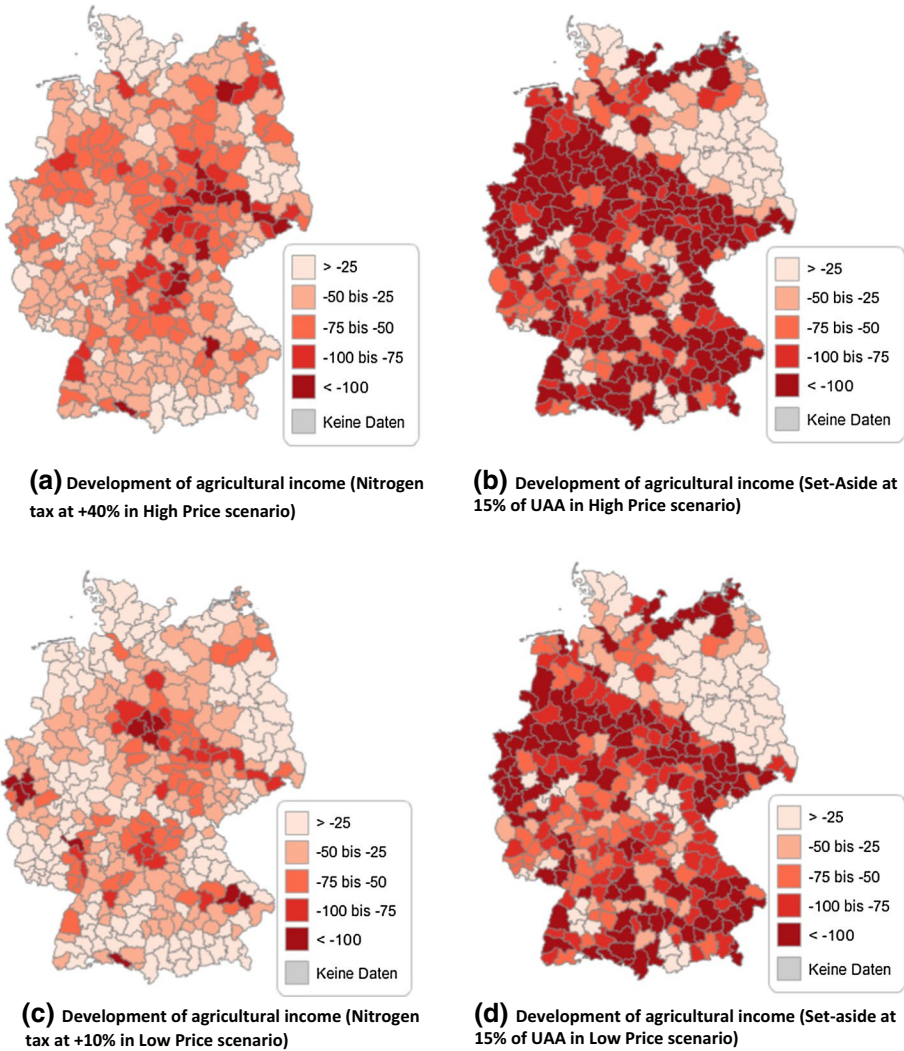
In the scenario baselines some set-aside area already exists (approx. 2% of UAA). The additional abatement of CO<sub>2</sub>e is not as high as compared to the baseline. However, losing the production factor land creates income losses. Thus, at small abatement levels, with relatively small additional abatement, the average costs per unit abated CO<sub>2</sub>e are high (at 390 and 500 EUR/t CO<sub>2</sub>e). With increasing abatement, the farmers abandon the production on productive high emitting land (e.g., cereals), which also impacts emitting husbandry (e.g., cattle by fodder crops, intensive grassland). The high abatement levels under higher set-aside quota result from the aggregated effects of the reduced crop production and the reduced livestock activities, as spill-over effect. With higher abatement levels both effects coincide and cause high income losses and a linear shape of the curve.

#### 4.7.5 The Impact of the Scenarios

Interpreting the graph in the direction from the cost axis (y-axis) to the abatement axis (x-axis) illustrates the impact of the global scenarios and the development of the global markets. For the same abatement options, the same cost level can reach significantly different abatement effects. For example, in the Higher Price scenario, the nitrogen tax costs about 190 EUR/t CO<sub>2</sub>e and abates less than 2 M t CO<sub>2</sub>e, whereas in the Lower Price scenario the nitrogen tax abates 9–10 M t CO<sub>2</sub>e for the same costs.

### 4.8 Impact at Regional Level on Agricultural Income

The regional analysis illustrates the differences between income losses of the regional producers at the same abatement level under the regimes of nitrogen tax or set-aside obligation. The development of agricultural income represents an aggregated indicator to conclude for changes of production patterns and intensities. For nitrogen tax, in both scenarios the loss in income accounts in most of the regions for less than 50 EUR/ha. For obligatory set-aside, in both scenarios the loss in income accounts in most of the regions for more than 100 EUR/ha (see Fig. 3a–d).



**Fig. 3** **a** Development of agricultural income (Nitrogen tax at +40% in High Price scenario). **b** Development of agricultural income (Set-Aside at 15% of UAA in High Price scenario). **c** Development of agricultural income (Nitrogen tax at +10% in Low Price scenario). **d** Development of agricultural income (Set-aside at 15% of UAA in Low Price scenario)

#### 4.8.1 Nitrogen Tax

In the Higher Price Scenario the income losses tend to be higher 25-50 EUR/ha because the higher price level provokes higher income losses than in the Lower Price Scenario. In regions with production focus on intensive cash crops the losses are higher, e.g. in North Western Germany, in Mecklenburg Western Pomerania or in the German Cereals Belt (reaching diagonally from North-Sea Coast to the border to Czech Republic in East-Central Germany). Here the low animal density reduces the possibilities to substitute the mineral

fertilizer by manure. Thus, the farmers' options to adapt to the increased nitrogen taxes by substitution are reduced.

In the Lower Price Scenario the single regional producers lose more than 100 EUR/ha. In these regions (e.g., Lower Rhine region, loess soil area in Lower Saxony) the farmers use a relatively high share of land for sugar beets. The strong decrease of sugar beet prices results in a significant loss of profitability for these regions.

#### 4.8.2 Obligatory Set-Aside

For the obligatory set-aside, the regional impact on farmers' income is comparable in both scenarios. Most of the farmers lose more than 100 EUR/ha because they abandon the production factor land on 15% of UAA. In regions with high set-aside rate in the baseline scenarios, the losses are much smaller since these regional producers already fulfill a part of the quota. Farmers in those regions in which production is in the baseline extensive and where marginal land is already abandoned are the "winners" of the policy set-aside quota. Their production is not influenced as much as in regions with low shares of set-aside in the baseline scenario. In regions with high profits, the instrument of obligatory set-aside causes losses of competitiveness. Thus this instrument strengthens the relative competitiveness of the less profitable regions.

## 5 Discussion

The findings of high marginal abatement costs and low maximum abatement potentials are in line with the studies which describe low effectiveness of market based instruments and control and command instruments (e.g., Shortle and Horan 2017; Ribaudo 2017). Thus, the results suggest that the investigated abatement options would require complementary abatement options to meet the anticipated abatement targets, which is in line with Ribaudo (2017). Ranging between 100–300 EUR/t CO<sub>2</sub>e (nitrogen tax) and 300–500 EUR/t CO<sub>2</sub>e (for set-aside), the computed abatement costs are higher than the abatement costs of other land-use based abatement options. With a maximum abatement potential of 4–7 t CO<sub>2</sub>e of nitrogen tax and set-aside, both measures show a relatively low ecological effectiveness. Thus, the two options are less effective and efficient than, for example, the restoration of peat land, for which Röder et al. (2015), computed a considerable maximum reduction of 25 M t CO<sub>2</sub>e at costs below 100 EUR/t CO<sub>2</sub>eM.

The simulated results do not consider the market feedback from the regional production to national and global markets. The environmental policies cause a decrease in production at the regional level. This reduction decreases the supply of agricultural commodities on the national and global markets and thus let the prices increase. As feedback, at the regional level, the increased prices change the impact of environmental policies. Monetary losses and abatement costs increase and thus shift the curve of MACs (Marginal Abatement Costs) upwards. This means that we underestimate the MACs with our computation.

Nevertheless, we believe that our estimation and interpretation of the MACs is appropriate. Within the global scenarios, the reduction caused by the instrument of obligatory set-aside is significant greater than the reduction caused by the nitrogen tax (Table 5). Correspondingly, the MACs for the obligatory set-aside are higher than the MACs of nitrogen tax. We assume that the increase of prices caused by market feedback shifts the curves upwards and increases the distance between the MACs of the two instruments. However,

we expect that the ranking between the MACs remains the same as in our analysis without market feedback. Thus, considering the market feedback increases the absolute values of the marginal abatement cost, but provides the same relative comparison between the measures, as we estimate with our analysis without market feedback.

The caveat of the missing consideration of market feedbacks results from the chosen top-down model linkage. Simulating the market feedback requires linking the three models in both ways (top-down) and bottom-up and an additional complex calibration to ensure consistent model reactions (cf. Sect. 3.1). The top-down-bottom-up of three different applied policy simulation models is beyond the scope of our paper and can be the objective for future modelling work.

## 6 Conclusions

The targets of the COP21 agreement demand the design and application of effective and efficient abatement options in Germany where agricultural production contributes, with more than 10%, a relevant share of GHG emissions. A comprehensive assessment of potential agricultural GHG abatement options requires the consideration of changes of global economy, of national agricultural markets and of impacts on regional agricultural producers.

Our policy analysis illustrates that uncertainties in the development of global economy and agricultural markets, as captured by the two global economic scenarios, cause different levels of ecological effectiveness and economic efficiency for the two policy instruments. The same instruments result at the same cost level in a large variation of abatement quantities driven by different global economic scenarios. In both global economic scenarios, the nitrogen tax is economically more efficient than the set-aside option. However, the differences in effectiveness and efficiency, resulting from the global scenarios would require an adjustment of the tax rate on nitrogen to reach a targeted abatement level. This represents a crucial challenge for market-based policy instruments (Shortle and Horan 2017).

The regional production conditions provoke different impacts of policy options on regional producers. Producers in extensive agricultural regions with high share of set-aside area the set-aside option would suffer fewer income losses than in intensive crop producing regions with small share of set-aside area. Also, the nitrogen tax results in high relative income losses for intensive crop producing regions. Thus, both policy instruments would require regional adjustment in order to avoid too high disadvantages of regional producers (Dalgaard et al. 2014).

Most of the linked economic models described in academic literature represent two economic or regional scales. In our study, we link three models to represent three economic and regional scales: the global economy, the agricultural markets and the regional production. Economic changes in each of these three scales can impact the effectiveness and efficiency of environmental policies. By linking the three models, we represent the three relevant scales in policy simulation models, which are specialized to address the research questions of interest.

Thus, the developed top-down economic model presented in this study could also be used for the assessment of other abatement options, which could be analyzed in future studies (e.g., the restoration of peat land, see Röder et al. 2015). The successful application to this study case and the multifold application of the linked models also promises fruitful applications to other currently relevant research questions and policies (e.g., concerning

food security, renewable energies or water pollution), which require the consideration of different economic scales: global, national and regional.

Compared between both global scenarios, the extensification option (compulsory set-aside), shows comparable impacts for different abatement levels. Compared between the two options for the nitrogen tax, the extensification option shows higher ecological effectiveness.

The results quantify the impacts of abatement options on producers in Germany under the changes in the global economic drivers and agricultural markets. In a Higher Price Scenario the land scarcity and increased food demand increase the prices (and yields) of the most important agricultural products in German agricultural markets. Agricultural producers increase their income by extending and intensifying the production of important commodities (e.g., cereals and dairy). In a Lower Price Scenario, the reduced land demand and filled yield gaps reduce the prices of agricultural products. Under income losses the producers extensify the production and thus reduce environmental pressure.

However, the regionally different production conditions provoke different impacts on regional producers. The extensification option could be favorable for producers in extensive agricultural regions with high share of set aside, whereas in intensive crop producing regions the nitrogen tax results in high relative income losses. Thus, both policy instruments would require regional adjustment in order to avoid too high disadvantages of regional producers (Dalggaard et al. 2014).

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