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Climate, energy and environmental policies in agriculture: Simulating likely farmer responses in Southwest Germany

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ABSTRACT

Agriculture in many industrialized countries is subject to a wide range of policy interventions that seek to achieve ambitious climate, energy and environment-related objectives. Increasing support for the generation of climate-friendly, renewable energy in agriculture, however, may lead to potential conflicts with agri-environmental policies aimed at land use extensification and landscape preservation. These potential trade-offs and inconsistencies in terms of policy implementation are not yet well understood, since conventional tools for agricultural economic assessment work on an aggregate regional level and do not fully capture the likely farmer responses when making a choice between investments in biogas production and participation in agri-environmental policy schemes.

We employed a farm-level model to analyze the reaction of a heterogeneous farming population in Southwest Germany to the incentives set by the German Renewable Energy Act (EEG), on the one hand, and the agri-environmental policy scheme MEKA, on the other. Our simulations indicate a potentially large decrease of MEKA participation due to biogas production supported under EEG. The success of the 2012 EEG revision in reducing the 'maizification' of agricultural landscapes will critically depend on the local demand for biogas excess heat. In any case, the EEG revision does not alleviate conflicts between the expansion of renewable energy and environmental considerations, but rather shifts priorities from the former to the later: the simulated reductions of maize areas are achieved by a considerable reduction in overall biogas production ("output effect"), and not by encouraging less maize-intensive feedstock mixes ("substitution effect").

Introduction

The last two decades have seen a shift of focus in agricultural policies from direct subsidization of agricultural production toward payments for public goods and services, environmentally-friendly production and greenhouse gas reduction. This shift addresses growing public concern for the externalities of food production, climate change and the conservation of traditional rural landscapes and farming systems. The motivation behind this development can, to a certain extent, be further attributed to the desire of policy makers to maintain a certain level of support for farming, and at the same time respond to the pressure to phase out coupled support arising in trade negotiations (Baylis et al., 2008; Harvey, 2003). In any case, the wide array of different policy objectives bears the danger that individual policy measures are narrowly targeted at one objective, while inadvertently counteracting another objective. This danger is even more prevalent if different political departments and scientific communities are targeting different objectives (Poe, 1997).

In order to reduce dependency on fossil fuels, reduce greenhouse gas emissions and – in some cases – create new markets for agricultural products, many countries have started promoting bioenergy and biofuel production. The Renewable Energy Directive of the European Union, the US Renewable Fuel Standard (RFS), or the National Alcohol Program (and its successors) and the National Program on Biodiesel Production and Usage (PNPB) in Brazil are only the most prominent examples (Sorda et al., 2010). As these policies have become more widespread, the focus of public debate has shifted from their positive effects for greenhouse gas mitigation and energy security toward undesired side effects through increased agricultural land prices and direct and indirect land use changes (Janda et al., 2012; Ziolkowska and Simon, 2011; Zilberman et al., 2014). On the one hand, including the emissions from direct and indirect land use change into the analysis

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leads to much lower GHG reduction potentials from bioenergies (Searchinger et al., 2008; Janda et al., 2012). On the other hand, these side effects may trigger serious environmental implications. In Brazil for example, increased biofuel production from sugarcane and soybean led to high deforestation rates and a loss of biodiversity through mono-cropping and the expansion of agricultural lands (Timilsina and Shrestha, 2010), while in the US a considerable amount of grassland was converted to cropland leading to more soil erosion, higher fertilizer uses and increased carbon dioxide releases (Hertel et al., 2010; Wright, 2013). Contributing to topsoil loss, grass- and wetland conversion, and water pollution and threatening biodiversity the Renewable Fuel Standard produces exactly the negative environmental externalities of agriculture that other federal agri-environmental policy programs such as the Conservation Reserve Program, the Conservation Security Program, the Grassland Reserve Program, the Wetlands Reserve Program, the Wildlife Habitat Incentives Program, or the Environmental Quality Incentives Program as well as many state-level initiatives intend to reduce (Baylis et al., 2008).

Similar conflicts can be expected to arise between the ambitious renewable energy targets set forth by the European Union and their members states (Klessmann et al., 2011) and the environmental and social objectives promoted by the second pillar of the EU Common Agricultural Policy (CAP). As a specific example, we analyze the side effects of the expansion of biogas production under the German Renewable Energy Act ('Erneuerbare-Energien-Gesetz', EEG) in this article. Intended to contribute to greenhouse gas mitigation, this package of various policy instruments has both triggered an intensification of agricultural land use – which has been labeled a "maizification" of German agriculture – and farmer complaints of excessive land rental prices. This recent land-use change is at odds with the objectives of the agri-environmental measures under the second pillar of the EU CAP, which promotes the reduction of chemical input use, conservation of biodiversity and upkeep of traditional agricultural landscapes. Especially, the expansion of silage maize areas for use as feedstock for renewable energy production has led to growing environmental concerns (Lupp et al., 2014; Pedroli et al., 2013; SRU, 2007). In an effort to reduce the environmental side-effects of biogas production, recent amendments to the German EEG introduced upper bounds for the use of maize silage, an incentive to diversify substrate mixes and obligatory co-generation of heat-and-power.

A number of policy studies have examined how farmers respond to the incentives set by the EEG and consequently adapt their agricultural land use – with rather ambiguous insights. Goemann et al. (2010), for example, found that the 2009 amendment of the EEG could not be expected to lead to a reduction of maize production. It would rather lead to an increase in production and aggravate land competition, especially in regions with high livestock densities. In contrast, Delzeit et al. (2012, 2012b) expect the 2012 amendment to have a dampening effect on silage maize production. Schulze Steinmann and Holm-Müller (2010) found that maize silage is the most profitable feedstock, even when considering higher transport costs for larger, more centralized biogas plants – confirming similar results from Austria by Walla and Schneeberger (2008). More generally, Sorda et al. (2013) investigated the development and spatial distribution of biogas production in North Rhine-Westphalia and Bavaria over the next 20 years. They expect biogas production to increase for another ten years under EEG 2009 conditions, while a reduction of feed-in tariffs would considerably slow down biogas expansion and favor smaller plant sizes. An increase in electricity remuneration would, however, not significantly increase electricity generation from biogas.

Little attention has been paid so far to the interaction of biogas support policies with agri-environmental policy schemes. To a certain extent, this is a consequence of the high level of aggregation in conventional policy simulation models. The studies cited above analyzed investment decisions in biogas electricity generation by modeling a regional decision-maker representing the aggregated decisions of all farmers in a municipality or an even larger geographical area. In theory, assuming perfectly functioning regional markets and inter-farm cooperation, the simulated centralized optimization of biogas plants and their spatial distribution is equivalent to the aggregate outcomes of individual farmer decision-making as long as the so-called aggregation error has been minimized (Hazell and Norton, 1986). In reality, farmer cooperation is limited and both, biogas investments and participation in agri-environmental schemes, are especially dependent on farm-specific circumstances (Walla and Schneeberger, 2008; Delzeit et al., 2012; Delzeit and Kellner, 2013; Wilkinson, 2011). Payments for environmental services are seldom the main source of farm income nor the main driver of agricultural production decisions, but rather taken up if they fit into the general production setup of the farm.

In the present article, we therefore shift the scale of analysis: we employ a farm-level model to simulate both, the decision for investment in biogas production and the decision to participate in agri-environmental measures, as an integral part of the individual farmer decision-making. To derive regional-level results, we run our model for all full-time farm holdings of our study area, the Central Swabian Jura in South-West Germany, instead of only for a few representative agents. Our simulation results illustrate the potential magnitudes of interaction and conflicts between biogas support and agri-environmental policies.

The paper is organized as follows: after discussing the potential conflicts between biogas support and agri-environmental policies in the study area (Section "Biogas support and agri-environmental policies in Germany"), we describe the modeling approach and the setup of the simulation experiments in Section "Data & methodology". We examine (Section "Results") and discuss (Section "Discussion") the effects of both types of policy interventions on biogas capacity, silage maize area, farm incomes, land rents, grassland extensification and diversification of crop rotations. We conclude by identifiying research priorities to improve precision and reliability of estimates (Section "Conclusions").

Biogas support and agri-environmental policies in Germany

Our analysis focuses on the potential goal conflicts between the federal Renewable Energy Act (Erneuerbare Energien Gesetz, EEG) and the agri-environmental policy measures of the second pillar of the EU Common Agricultural Policy (CAP), which have been implemented under the name "Compensation Scheme for Market Easing and Landscape Protection" (Marktentlastungs-und Kulturlandschaftsausgleich, MEKA) in the state of Baden-Württemberg. The EEG aims to contribute to climate change mitigation, a global environmental goal, via the promotion of renewable electricity production, e.g. from biogas. As a consequence, it incentivizes the intensification of agricultural production, leading to the tendency of biogas farmers to specialize in silage maize production with adverse consequences to biodiversity and agricultural landscapes. Moreover, high profit margins and guaranteed revenues have driven up rental prices for farmland and favor large production units. The MEKA scheme, in contrast, comprises a portfolio of very diverse measures aiming mainly at environmental benefits that are rather local in scope. Goals include the conservation of biodiversity, landscapes resulting from traditional farming practices, and traditional animal breeds as well as a reduction of pesticide use – all generally associated with land-use extensification, rather than intensification of production.

The Renewable Energy Act (EEG)

The EEG[1] was created in the year 2000 as a successor to the Electricity Feed Act ("Stromeinspeisegesetz", SEG) of 1991 and underwent major revisions in 2004, 2009 and 2012. It obliges electricity providers to buy electricity produced from renewable energy sources at a fixed price, which is specific to the type of energy source used and defined so as to make electricity production from this source profitable. At the same time, the price is reduced by a certain percentage every year in order to set incentives for technological development increasing production efficiency. The price valid in the year a biogas plant went into production is guaranteed for electricity generated from this plant for the following 20 years. In addition, the guaranteed basic price decreases by volume following a system of four tiers (respectively five tiers from 2012).

While the price levels for biogas electricity set by the original version of the EEG enabled municipal biogas plants operating with organic waste to work profitably, they were too low to spark substantial investment in the agricultural sector. As a consequence, the 2004 revision of the EEG introduced a bonus for the use of energy crops, plant material and manure (the so-called NaWaRo bonus). This amendment resulted in a biogas boom in German agriculture (FNR, 2009). Additionally, the 2004 amendment created a reward for the external use of excess heat from biogas plans, the combined heat and power (CHP) bonus.

After the intensification of energy maize production received increased public attention, the 2009 amendment[2] introduced an additional manure bonus, paid on top of the NaWaRo bonus, if at least 30% of the feedstock consisted of farm-yard manure. Apart from this, the amendment mainly redefined guaranteed prices and bonuses, generally favoring smaller electricity volumes over larger ones.

The most recent EEG amendment,[3] approved in 2012, constitutes a major revision to the incentive structure for biogas production. While the general system of guaranteed prices and volume tiers was maintained, NaWaRo and manure bonuses were replaced by specific prices for feedstock classes, where Class I comprises energy crops and Class II, manure, legumes and material from landscape conservation cuts. The price received is then calculated according to the share of feedstock classes used in the production mix. To receive remuneration under EEG 2012, feedstock must consist of no more than 60% of maize silage, corn-cob-mix, or cereal grains. The external use of produced heat of at least 25% in the first year and 60% in the following years is made obligatory unless at least 60% of the feedstock used is manure. As a consequence, the CHP bonus has been abolished. Further, a special higher and untiered guaranteed price for small biogas plants up to 75 kW with at least 80% manure use was introduced.

The various amendments of the EEG reflect how the intentions behind renewable energy legislation have changed over time. At the onset, legislators focused on increasing incentives for biogas plants, while recently the emphasis has been much more on avoiding perceived adverse consequences from the biogas boom.

The Compensation Scheme for Market Easing and Landscape Protection (MEKA)

The Compensation Scheme for Market Easing and Landscape Protection ("Marktentlastungs-und Kulturlandschaftsausgleich", MEKA) is an agri-environmental support scheme implemented by the state government of Baden-Württemberg within the legal framework defined by the EU in Council Regulations (EEC) 2078/92 and (EC) 1257/1999, which forms part of the second pillar of the EU Common Agricultural Policy. EU regulations require farmers to commit to a measure for at least five years and compensation payments to be calculated based on the additional cost of implementing the measure compared to current obligatory regulations.

So far, there have been three phases of the MEKA program: MEKA I from 1994 to 1999, MEKA II from 2000 to 2006, and MEKA III from 2007 to 2013. For each phase, the scope of support measures and levels of support underwent substantial revisions. MEKA III, the most recent phase, includes 20 measures, which are listed under the seven categories: (A) environmentally-friendly farm management, (B) conservation of agricultural landscapes, (C) conservation of especially endangered land uses, (D) abandonment of synthetic chemical inputs, (E) extensive and environmentally-friendly plant production, (F) use of biological plant protection, and (G) conservation of specific protected habitats (MLREV, 2011).

Our analysis in this paper will focus on four measures: measure 2 from category A rewards the diversification of crop rotations with, at present, 20 Euro per ha. To do so, it requires the production of at least four crops, each with a minimum share of 15% of their total arable area and restricts maize production to 40% of the area. The other three measures are part of category B and related to extensive grassland use. Commitment to any of these measures requires the farmer to refrain from grassland conversion and non-specific use of chemical plant protection on grasslands. Under measure B1, farms that restrict livestock density to under 2 livestock units (LSU) per ha, abstain from grassland conversion, and mow 5% of their committed grassland area after the 15th of June receive 50 Euro per ha of qualifying grassland. Measure B2 imposes maximum livestock densities of 1.4 LSU per ha of agricultural area, 1.4 grazing livestock units (gLSU) per ha of fodder area, and a minimum density of 0.3 gLSU per ha of fodder area. It awards 100 Euro per ha of grassland committed. The third measure, B4 is result-oriented (Matzdorf and Lorenz, 2010; Burton and Schwarz, 2013) and awards 60 Euro per ha if at least four out of a catalog of 28 characteristic plant species can be observed on the committed extensive grassland area.

Data & methodology

Study area

We assess the potential conflict between these agri-environmental and renewable energy support schemes in the Central Swabian Jura (Fig. 1), a low mountainous area (650–850 m.a.s.l.) located between Stuttgart and Ulm, covering 1300 km^2 and accounting for about 80% of the district of Reutlingen and 33% of the district of Alb-Donau. Agricultural production in the area is constrained by shallow soils and a comparatively harsh climate (mean annual temperatures around 7 °C, mean annual precipitation 800–1000 mm) and characterized by a relatively balanced mix of crops and livestock production. A sequence of winter barley, winter rapeseed, winter wheat and summer barley is the dominant crop rotation, with some silage maize, clover and field grass production intermixed for dairy and cattle farmers. For the year 2012, Dederer and Messner (2011) report 95 biogas plants

[1] Bundesgesetzblatt, Teil 1, Nr. 13 (2000), Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG) sowie zur Änderung des Energiewirtschaftsgesetzes und des Mineralölsteuergesetzes. 31. MÄrz 2000, pp. 305–309.

[2] Bundesgesetzblatt, Teil 1, Nr. 49 (2008). Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich und zur Änderung damit zusammenhÄngender Vorschriften. 25. Oktober 2008, pp. 2074–2100.

[3] Bundesgesetzblatt, Teil 1, Nr. 42 (2011). Gesetz zur Neuregelung des Rechtsrahmens für die Förderung der Stromerzeugung aus erneuerbaren Energien. 28. Juli 2011, pp. 1634–1678.

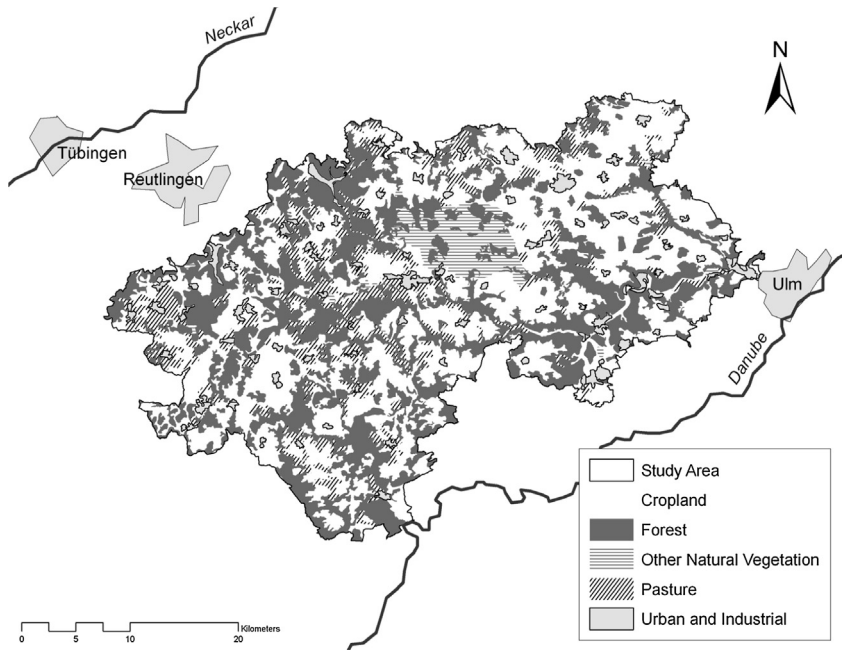

Fig. 1. Study area (land use adapted from CLC, 2009).

with a total installed biogas capacity of 28,206 kW in the two districts containing our study area. Moreover, the area provides several landscape amenities (biosphere reserve) and enjoys fame as a tourist attraction (hiking, skiing, thermal baths, etc.)

Farm decision model

To analyze the effect of EEG and MEKA on agricultural land use, we simulate the investment and production decisions of every full-time farm of the area using the farm-level model that was developed in Troost et al. (2012) and Troost and Berger (2014) for this study area. The model assumes that farmers allocate their production factors (land, labor and capital) such that they maximize expected farm income given their individually specific resources and production options, sales and input prices, and the technical and agronomic constraints governing agricultural production. This decision is implemented as a mixed integer programming (MIP) problem and solved for each full-time farm in the study area.

The objective function to be maximized represents expected farm income as a function of revenues from crop production R_c, animal husbandry R_h, biogas production R_b and received premiums from EU CAP and MEKA schemes R_p subtracting variable costs V, fixed costs (respectively annualized investment cost for new investments) F, and the balance of interest paid and received I as shown in Eq. (1). Here $\mathbf{p}_e$ denotes expected prices, $\mathbf{y}_e$ expected yields, $\mathbf{a}$ crop and grassland activities, $\mathbf{f}$ the part of the crop that is used as animal feed, $\mathbf{h}$ animal husbandry activities, $\mathbf{k}$ biogas production, z the first year of biogas production, $\mathbf{M}$ machinery owned and employed, $\mathbf{B}$ buildings and infrastructure owned, $\mathbf{A}_r$ the amount of land rented in and l hired labor.

$$max\,!\quad \pi_e = R_c(\mathbf{p}_e, \mathbf{y}_e, \mathbf{a}, \mathbf{f}) + R_h(\mathbf{p}_e, \mathbf{h}) + R_b(\mathbf{k}, z) + R_p(\mathbf{a}, \mathbf{h}) - V(\mathbf{p}_e, \mathbf{a}, \mathbf{h}, \mathbf{f}, \mathbf{M}, l) - F(\mathbf{p}_e, \mathbf{B}, \mathbf{M}, \mathrm{A}_r) + I \tag{1}$$

The model as used in the present article allows for investments in farm machinery and biogas plants. Crop production comprises winter wheat, winter rapeseed, summer and winter barley, silage maize, field grass production and fallow on arable land as well as grassland cultivation at four levels of intensity (abandonment, extensive use, 2 or 3 uses per year) and with five potential uses: hay, grass silage, pasture, cutting of fresh grass for direct feeding as well as late and very late maintenance cuts compatible with MEKA requirements. The agents distinguish nine different soil classes for arable land, which affect crop yields and tractor power required for field work. Crop yields have been simulated using the crop modeling package Expert-N based on the parameterization presented in Aurbacher et al. (2013). Grassland is considered a separate soil class, which has not been subdivided further. Grass yields depend only on management and are based on grass regrowth functions calculated from data given in Berendonk (2011). Crop production is constrained by agronomic limits to crop shares in the rotation and preceding-following crop relationships as well as the field work capacity of the farm, which is calculated as a function of labor and machinery endowments as well as expected days with suitable weather (see Troost and Berger, 2014 for a detailed discussion).

Animal production comprises dairy production, calf and heifer raising, bull fattening, suckler cow herding, piglet production and raising, and pig fattening and is constrained by existing stable capacities and the manure usage of crop production. Animal feeding requirements have been formulated in terms of nutrient and fiber demands following LfL (2010, 2011) allowing the farm agent a great deal of flexibility in the combination of bought and self-produced fodder. Other inputs and labor demands are based on KTBL (2010). Sales, input and machinery prices are based on LEL (2010, 2011, 2011), destatis (2012) and KTBL (2010).

The complete MIP matrix representing the investment and production decision problem of a farmer in the area comprises around 6900 variables in about 3800 equations. A full model description including all equations can be found in the model documentation (see Troost, 2014). In the following sections, we concentrate on describing the representation of biogas production and the EEG and MEKA restrictions in the model most relevant to the present article.

This MIP problem is solved for each full-time farm in the area setting capacities (and a few farm-specific matrix coefficients) according to the observed characteristics of the farm. The model is implemented using the agent-based software package MPMAS (Schreinemachers and Berger, 2011), although the model as used in the present article abstracts from any agent–agent interactions

(i.e. it is a nonconnected agent-based model in the definition of Berger et al., 2006). In keeping with MPMAS conventions, we will use the term farm agent to refer to the model representation of an individual farm throughout this article.

Troost and Berger (2014) created statistically representative agent populations for the study area for the years 1999, 2003, and 2007 based on Agricultural Census and Farm Structure Survey data (FNZ, 2010), a farm survey as well as population statistics (destatis, 2011, 2012, 2012, 2012). The simulations in this article use the sample of agent populations representing the 533 full-time farm households observed in 2007.

Biogas production in the model

As information about the exact number of biogas plants and their distribution over farm types in the study area has not been recorded, we decided to initialize the model without any existing biogas plants.[4] As a consequence, production of biogas electricity requires an investment in biogas plant capacity in our model setup in any case. Contrary to other studies (Delzeit et al., 2012; Sorda et al., 2013), our implementation does not restrict investment options to a small discrete set of predefined plant sizes, but rather let farm agents freely choose the income-maximizing capacity given their individual technical constraints (i.e. farm size, labor and machinery endowments, soil types, etc.) To reflect economies of scale, investment costs were implemented as a linear function of plant size estimated at 394, 249 € +2459 €/kW × capacity [kW] based on data from Stenull et al. (2011) and FNR (2010). As we had no information available on the cash reserves of individual farms, we also neglected any form of down payments on biogas plants and used a rather moderate interest rate of 6% on foreign capital. We generally assumed a lifetime of 20 years for biogas plants following KTBL (2010), though the actual lifetime used in the investment calculus of the model may be lowered to the expected remaining lifetime of the farm, which in some of the tested model configurations (see Section "Simulation experiments" and Appendix B) depends on the farm manager's or his/her potential successor's age.

Maintenance of the biogas plant requires 504.4 h of labor independent of plant size (FNR, 2006) and 132.74 Euro per kW each year for repair, laboratory analysis and insurance (Stenull et al., 2011). Additionally, we considered that a replacement of the engine for 880 Euro is usually necessary after ten years (FNR, 2006).

In the model, biogas electricity can be produced from maize silage, grass silage, wheat silage as well as from pig or cattle manure. This feedstock must be produced on the agent's farm as trade of biogas feedstock is not included in our present analysis. Electricity yields for different types of feedstock have been calculated as a product of electric efficiency, the specific heating value of methane of 10 kWh/m^3 (FNR, 2010) and the feedstock specific methane yield calculated from the KTBL production standards database (KTBL, 2010) (see Table 1). Heat yields were calculated correspondingly using thermal efficiency. We assumed an electrical efficiency of 35% and a thermal efficiency of 45% (FNR, 2006; KTBL, 2009), and that 40% of the produced heat is available for external use (Stenull et al., 2011).

Labor demand for biogas production (a_g^{uGH}) amounts to 0.5 min/t for manure and 5 min/t for other feedstock (FNR, 2006). Input electricity equivalent to 7% of the generated electricity is consumed following KTBL (2010). Details on the implementation of biogas production in the MIP can be found in Appendix A.

Agents can sell their electricity either on the free market for 30% of the normal consumer electricity price (following long-term spot market price development observed at the European electricity exchange in Leipzig), or for the guaranteed price under EEG 2009 or EEG 2012 conditions, depending on the scenario. A comparison of guaranteed prices under the two EEG versions for plants established in the year 2012 are shown in Table 2. (For consistency, we compare the two EEGs for the same year, cf. Section "Simulation experiments").

Implementation of remuneration from EEG 2009 is straightforward in the model: base rate and NaWaRo bonus were applicable to all types of feedstock considered in our simulation study. The manure bonus was paid if at least 30% of the feedstock mass comes from manure, and the CHP bonus was paid for the electricity production equivalent to the amount of heat sold. Unfortunately, we have currently no information on the marketing opportunities of heat for individual farmers in the area. We therefore assessed two simulation scenarios covering the potential extremes: Either every or no agent had the opportunity to sell excess heat (scenarios with and without renewable heating markets, respectively).

The remuneration scheme of EEG 2012 could not be straightforwardly implemented in mixed integer programming: ensuring that the mixture of Class I and Class II prices corresponded to the feedstock mixture in all volume tiers and that agents did not shift Class I electricity sales to the <150 kW tier and Class II electricity sales to the 150–500 kW tier (exploiting the more favorable price relationship) involved multiplication of solution variables, making the problem non-linear. This issue was circumvented by discretization: we predefined mixtures at a resolution of 10% intervals and allowed linear combination of two adjacent mixtures, minimizing the degree of potential tier shifting while still allowing flexible feedstock mixes.

To receive EEG 2012 payments, agents whose feedstock consisted of less than 60% manure were obliged to use 25% of the produced heat in the first year and 60% in the following years. Additionally, the combined feedstock share of maize and (coarse) grains was limited to a maximum of 60% of total mass content. Alternatively, agents could opt for a small plant (≤75 kW capacity) and use at least 80% manure. As a consequence, in the scenario without renewable heating markets, a manure share of at least 60% was required to receive any EEG 2012 payments at all. Details on the implementation of EEG remuneration in the model can be found in Appendix A.

MEKA

In the model, the conditions for agent participation in the A2, B1, B2, and B4 measures of the MEKA III program have been implemented with the following simplifications: grassland conversion was not allowed in our simulations due to the state-wide ban enacted in 2011. In addition, grassland management practices parameterized in the model did not consider changes in pesticide use explicitly. Moreover, grassland use of extensive intensity with late cuts was assumed to comply with conditions of MEKA measure B4, as the exact species composition was not captured in the model. Apart from these necessary simplifications, the modeled conditions to receive MEKA payments implemented correspond to the real-world restrictions described in Section "Biogas support and agri-environmental policies in Germany". Details on the implementation can be found in Appendix A.

Simulation experiments

For policy analysis, we simulated the investment and production decisions of farm agents in the study area. Price expectations of agents were set to the long-term price average (2000–2009) in real

[4] Note: In Troost and Berger (2014) existing biogas plants in 2007 were initialized based on expert estimation. While we found this acceptable for climate change adaptation analysis, we preferred using a different type of analysis here where biogas production is at the center of the analysis.

Table 1
Biogas yields and methane contents of selected substrates (KTBL, 2010).

	Cattle slurry	Pig slurry	Maize silage	Grass silage	Wheat silage
Biogas yield (m^3/t)	30	20	200	190	190
Methane content (%)	55	60	52	53	53
Dry matter (%)	10	6	33	35	33
Organic dry matter (%/DM)	80	80	95	90	95

Table 2
Guaranteed prices (euro cents) per kWh of electricity for plants established in 2012 under EEG 2009 and EEG 2012.

kW_{el}	EEG 2009			EEG 2012		
	Base-rate + NaWaRo bonus	Manure bonus	CHP bonus	Class I	Class II	Small manure plants
≤ 75						25
≤ 150	18.1	3.9	2.9	20.3	22.3	
150–500	15.7	1	2.9	18.3	20.3	
500–750	11.9		2.9	16	17	
750–5000	11.9		2.9	15	16	

terms of 2009 and EU CAP regulations were implemented as valid in 2012. With this setup, we compared six hypothetical situations for the year 2012 combining three EEG scenarios (EEG09, EEG12 and no EEG at all) with two MEKA scenarios (MEKA III or no MEKA at all). Both, EEG09 and EEG12 consider the guaranteed prices set by the respective EEG version for the year 2012. As a consequence of neglecting existing biogas plants and cash constraints to investments, simulated outcomes of agent investments in biogas plants represent the upper bound of the regional investment potential for biogas plants based on their profitability in each scenario.

The farm-level model used in this analysis is akin to a process-based model in that it explains the phenomenon of interest (policy effects on regional biogas production and land use) by disaggregating it to theoretically known (or empirically observable) processes (the agronomic and technical relationships determining the production conditions faced by farmers in the region) in order to derive conclusions about unobserved situations (counterfactual policy scenarios). Typically, such farm-level models are subject to considerable uncertainty as the necessary data is not available in the required depth and breadth for a full region (Buysse et al., 2007). Standard technical coefficients have to be used, parameters have to be chosen *ad hoc*, parameter variability has to be neglected, processes are omitted and other process representations are uncertain or incomplete. Despite a comparably comprehensive database, our model is no exception to this rule.

Good modeling practice requires to clearly communicate this uncertainty to readers and analyze it in order to assess the robustness of results and, on the long run, improve process understanding (Jakeman et al., 2006). Given the typically high uncertainty in agricultural agent-based models, Berger and Troost (2014) suggest to refrain from identifying a single parameter combination that best fits observation data (which would neglect all sources of model uncertainty), but rather present the outcomes of simulation experiments as ranges or distributions over all parameter combinations that can be considered potential representations of reality. Following this approach, Troost and Berger (2014) used a conservative calibration approach and identified 19 parameters in the Central Swabian Jura model that have to be considered uncertain after calibration.

To efficiently cover the parameter space spanned by these 19 parameters in a feasible number of model runs, we first ran an elementary effects screening (Campolongo et al., 2007) to identify those of the 19 parameters with the highest influence on the outcomes relevant for the present analysis, namely the installed biogas capacity, maize areas, land use and MEKA participation. We identified 14 important parameters (see Appendix B), 13 of which were used to construct a Latin hypercube sample (LHS) with 30 repetitions. The CHP parameter, which switches markets for renewable heating on or off, stood out as the most important parameter by far. As a consequence, we decided to repeat the full sample for both options instead of including this parameter in the LHS, i.e. our experimental design comprised a total of 60 repetitions per scenario. With six scenarios this leads to a total of 360 model runs.

Results

In this section, we present our simulation results in four steps: first, we assess the differences in investments in biogas capacity and silage maize area between EEG 2009 and 2012, before analyzing the interaction between EEG and MEKA policies. To assess the potential impacts of policy measures on the performance of rural land markets, we will then take a look at simulated shadow prices of agricultural land and finally assess effects on farm incomes.

Effects of the EEG

Table 3 shows the investment in production capacity for biogas electricity simulated under the three EEG scenarios. For each EEG scenario, the upper line represents the situation where all agents can sell biogas heat (scenario with renewable heating market) and the lower line the scenario where no agent can sell biogas heat (scenario without renewable heating market). Each line shows the mean and standard deviation of the distribution of simulated variables over the 30 repetitions of the Latin hypercube sample. We observed a considerable variation in simulated capacities between repetitions, but differences between EEG scenarios have a consistent impact across repetitions and are thus robust against parameter uncertainty. In the model, the 2012 revision of the EEG led to a reduced investment in biogas capacity of 3–12% compared to the 2009 version of the EEG when we assumed that all agents had the opportunity to sell the heat from their plant, and to a reduction of 91–94%, when we assumed no agent could sell the heat. Without the EEG, no agent would have invested in a biogas plant at current energy price levels. The reduced total biogas capacity in our simulations was mainly caused by a lower number of agents investing in biogas plants, while the average capacity per biogas plant was only lower under EEG 2012 without heat sales.

The simulated differences in biogas production had direct consequences for crop production in the study area. Simulated silage maize area experienced a three- to five-fold increase compared to the situation without EEG support. Again, simulations for EEG 2009 and 2012 were rather similar with only slight reductions in maize area for EEG 2012 as long as we assumed every agent to be able

Table 3
Simulated investments in biogas plants and area used for silage maize production by EEG scenario and with MEKA payments (mean and standard deviation over 30 repetitions).

EEG scenario	Renewable heating market	Number of investors	Average plant size [kW]	Total capacity [kW]	Silage maize area [ha]
EEG2009	Yes	254 ± 42	101 ± 3	25, 703 ± 4302	8295 ± 1251
	No	195 ± 38	101 ± 4	19, 729 ± 3952	7394 ± 1204
EEG2012	Yes	223 ± 39	108 ± 4	24, 086 ± 4237	7969 ± 1220
	No	21 ± 5	75 ± 0	1539 ± 381	2116 ± 262
No EEG	Yes	0 ± 0	0 ± 0	0 ± 0	1821 ± 244
	No	0 ± 0	0 ± 0	0 ± 0	1821 ± 244

Table 4
Predicted shares of different feedstock in total biogas production in the study area under different EEG scenarios (mean and standard deviation over 30 repetitions).

EEG	Renewable heating market	Feedstock shares		
		Grass silage	Maize silage	Manure
2009	Yes	33 % ± 3.6	39 % ± 4.4	28 % ± 1.5
2009	No	29 % ± 3.3	41 % ± 4.5	30 % ± 1.7
2012	Yes	36 % ± 3.3	39 % ± 4.1	25 % ± 1.8
2012	No	4 % ± 1.2	16 % ± 1.2	80 % ± 0.0

to sell biogas heat. Without being able to sell heat, silage maize production was only slightly higher than in the no EEG scenario.

The composition of the feedstock used for biogas production is shown in Table 4. The average plant size and feedstock composition for EEG 2012 in the absence of heat sales indicates that only the small manure plant category (≤ 75 kW with ≥80% farmyard manure) offered a profitable option for agents without CHP potential.

EEG and MEKA

Table 5 shows the simulated effect of the different EEG scenarios on the area committed to the four MEKA support schemes included in our simulations. The strongest effect was observed for the A2 measure that rewarded crop diversification, i.e. requiring at least four crops, each with an area share of at least 15% in the crop rotation. Without EEG support, as well as under EEG 2012 without renewable heating market, nearly all agents committed their arable land to this environmental policy measure, which is about four times the area committed in the EEG 2009 scenario with renewable heating markets.

A similarly strong reduction of committed area in the scenarios with biogas expansion could be observed for measure B4, which rewards conservation of abandoned grasslands. For the support of extensive grassland use, we saw a slight decline in area committed to measure B1, while the area agents committed to B2 increased slightly.

The effects of the MEKA schemes that can be induced from the counterfactual scenarios without any MEKA payments were rather small. MEKA support reduced the installed capacity for biogas electricity production by 0–5%, with the exception of the EEG 12 scenario without renewable heating markets, where MEKA support resulted in a reduction of up to 16%.

Table 5
Simulated area registered for participation in the four considered MEKA measures depending on EEG scenario and with MEKA payments (mean and standard deviation over 30 model runs).

Scenario	Renewable heating market	Area [ha] committed to MEKA measure	
		A2	B1
EEG2009	Yes	4396 ± 1430	4399 ± 417
	No	6589 ± 1724	4903 ± 366
EEG2012	Yes	4808 ± 1445	4978 ± 358
	No	17, 037 ± 941	6391 ± 334
No EEG	Yes	17, 304 ± 925	6263 ± 315
	No	17, 304 ± 925	6263 ± 315
		B2	B4
EEG2009	Yes	9856 ± 302	1452 ± 435
	No	9749 ± 331	2100 ± 439
EEG2012	Yes	9467 ± 273	1677 ± 406
	No	8529 ± 264	5844 ± 164
No EEG	Yes	8688 ± 240	5974 ± 144
	No	8688 ± 240	5974 ± 144

Effect on land rents

Since German farmers tend to rent out rather than sell their land when leaving farming, the land rental market is the most important vehicle to facilitate structural change in agriculture. To capture the effects of EEG and MEKA support on the development of land rental prices, we computed the shadow prices of arable and grassland soils for each agent. The shadow price, i.e. the marginal production value of land in each soil type, was estimated by resolving the production and investment decision of each agent with an additional unit of this type of soil and observing the additional income that could be obtained from using the additional amount of land. Note that the individual shadow price is a marginal value calculated for the first hectare an agent rents in; it does not take into account the balancing of demand and supply on land rental markets, where land is also typically transferred in greater units. It can therefore not be expected to equal the observed rental prices in the study area (in our simulations the median shadow price for arable land is about 2–4 times the currently observed rental price): still, the simulated shadow price gives a highly useful indication of the effect of policy measures on the agent's willingness-to-pay for agricultural land.

We compared the simulated median shadow price of the agents between scenarios. Table 6 summarizes the different relative effects of EEG and MEKA policy scenarios on the marginal production value of the most frequent soil type of arable land (mostly rendzic leptosols) and grassland under the two possible scenarios with and without renewable heating markets. The median shadow prices of the scenario without MEKA and without EEG have been set to 100 for each of the 30 repetitions, and the values of the other scenarios have been expressed relative to this. The table shows mean and standard deviations of relative values over repetitions.

The scenarios under EEG 2009 and EEG 2012 with renewable heating markets showed high levels of biogas production together with high shadow prices of land. The median shadow price doubled compared to the scenario without any EEG support for arable land, with even stronger effects for grassland. Without renewable heating markets, the median shadow price remained nearly unaffected

Table 6
Relative effects of EEG and MEKA on the median shadow price of land (mean and standard deviation over 30 repetitions). Values relative to the scenario without MEKA and without EEG, which was set to 100 for each repetition.

MEKA	EEG	Soil class 0		Grassland	
		With ren. heating market	No ren. heating market	With ren. heatingmarket	No ren. heating market
Yes	2009	207 ± 49	140 ± 18	802 ± 188	577 ± 103
	2012	192 ± 55	104 ± 1	762 ± 201	288 ± 24
	No	104 ± 1	104 ± 1	284 ± 22	284 ± 22
No	2009	207 ± 52	137 ± 19	693 ± 203	427 ± 115
	2012	191 ± 60	100 ± 0	631 ± 230	104 ± 3
	No	100 ± 0	100 ± 0	100 ± 0	100 ± 0

under EEG 2012 and showed lower, but still considerable increases under EEG 2009. The effect of MEKA support on the shadow price of arable land was negligible, but strong increases in production value could be observed for grassland areas.

Effects on income

Fig. 2 depicts the income effects under the various EEG implementations. The box plots show the distribution of the absolute income difference with the respective EEG implementation compared to a scenario without any EEG, over all agents and repetitions. A change of income, of course, can only be expected if agents invest in biogas plants: Agents have therefore been grouped in the figure according to the scenarios in which they invested in a biogas plant: (i) never, (ii) only with EEG 09, (iii) only with EEG 12, or (iv) under both EEG 09 and EEG 12. In general, our simulation experiments suggest income gains between 200 and 600 Euro per ha under EEG 09 and EEG 12 with heating markets. Agents which invested only in one of the two market scenarios tended to have lower income gains, in most cases not reaching 200 Euro per ha, an observation that also holds for investors under EEG 12 without heating markets.

Fig. 3 shows the simulated income effects of the MEKA scheme under the three EEG and two heating market scenarios. Box plots indicate the distribution of per-ha income effects over agents and repetitions, in which potential income effects concentrated around 10–60 Euro per ha.

Discussion

Our simulation results suggest interactions between EEG and MEKA policy schemes that go in both directions. If biogas support is successful in encouraging farmer investments in biogas generation, it simultaneously and considerably decreases participation in grassland conservation and crop diversification measures under MEKA. Whether the EEG revision of 2012 substantially changes the picture apparently depends on the local demand for excess heat from biogas generation. As explained above, empirical data on local energy markets are not yet available to accordingly parametrize the model. If local demand is too low to satisfy the co-generation requirement of the new EEG, only few farmers are likely to opt for a small manure plant and invest in biogas plants. As a consequence, the silage maize area will be considerably lower and the effect on MEKA participation will be minor. Given the importance of grassland in our study area, the newly introduced 60% cap on maize silage as feedstock should have only small effects, according to our simulations. Indeed, the average feedstock share of maize silage in the EEG 2009 scenarios was only 40% and changed little in the EEG 2012 scenario with heating markets. The impact of the biogas support policy on farmer income should be far greater than the impact of the MEKA measures, at least for those farmers who are able to invest in biogas production. In simulation experiments, MEKA payments kept only a few agents from investing in biogas plants.

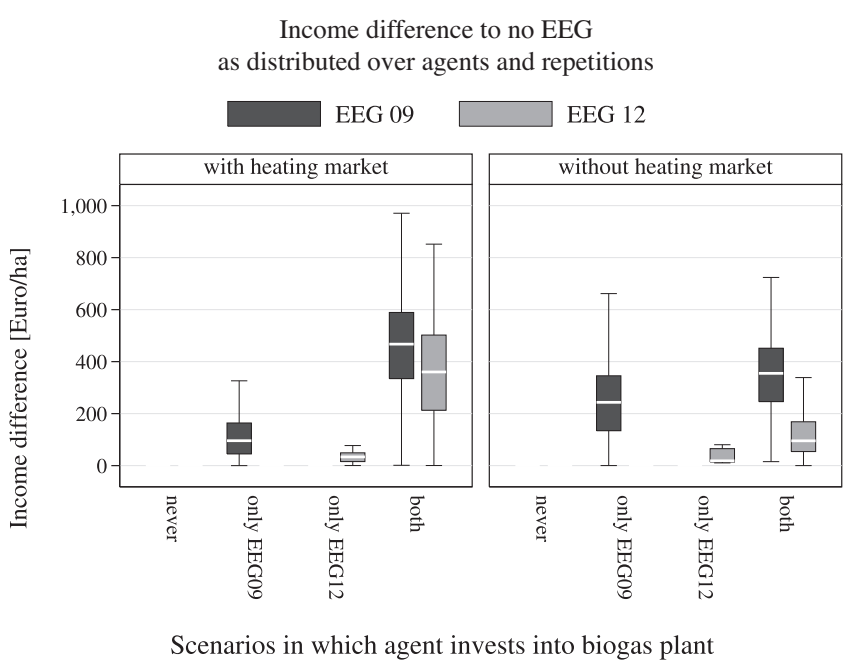

Fig. 2. Distribution of simulated absolute income effects of two EEG versions compared to no EEG support over agents and repetitions. Agents were grouped depending on the scenarios in which they invest in biogas capacity.

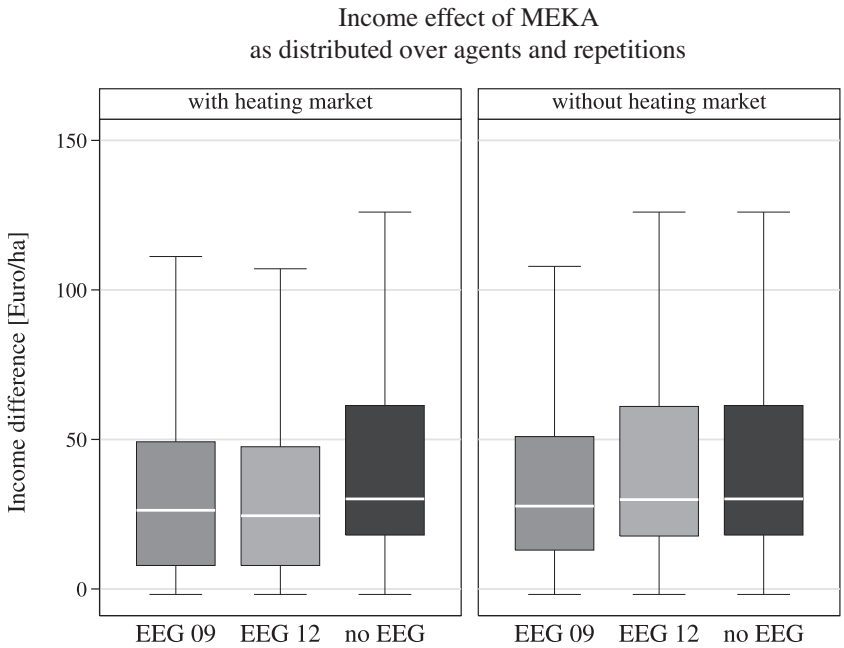

Fig. 3. Distribution of simulated absolute income effects of MEKA over agents and repetitions depending on the EEG scenario.

Overall, the potential policy effects on farm incomes showed great differences between agents. With regard to biogas support it has to be considered that, at maximum, about half of the full-time farm agents actually had the potential to benefit from biogas production at all. This heterogeneity in policy impacts bears the potential to accelerate structural change in agriculture, which is also illustrated by the doubling of the median shadow prices of arable land and the corresponding 6–8 fold increase in median shadow prices of grassland. While the simulated shadow prices cannot be directly translated into land rental prices, they indicate a strong increase in the willingness-to-pay for farmland. Note that the MEKA scheme increased the value of grassland in our simulations, albeit starting from rather low levels.

Although our simulation experiments yielded a number of interesting insights, the interpretation of the results is subject to several limitations: we assessed farmer investment decisions in renewable energy plants by means of one-year simulation scenarios under purely short-term profitability considerations. Due to the current lack of more precise empirical data, we could not capture that some farmers in the study area have already built biogas plants in the past. Liquidity constraints, farm life-cycles and uncertainty will most likely preclude immediate investments in many cases, while the yearly reduction of guaranteed prices tends to make investments less profitable in the future (depending on the development of investment costs and substrate costs). In this respect, our simulation scenarios reflect the upper bounds of on-farm investment in biogas plants under the different EEG conditions. The next step in our simulation analysis will therefore be to run recursive-dynamic simulations of 10–20 years. This is possible with our model setup, but requires further data and model validation before it can be meaningfully employed. Further, the distribution of income effects showed a number of farm agents who can only expect small gains from biogas production and it seems uncertain whether a farmer in reality would be willing to take the investment risk for rather modest income gains.

Currently, our simulation model abstracts from inter-farm cooperation and local trade of silage, due to limited empirical information on farm cooperation and fragmented local markets. The simulations showed relatively small biogas plant sizes and a relatively high number of agents who invest in individual biogas plants. In reality, farmers might also choose to jointly build larger biogas plants.

MEKA participation was hard to validate, as exact measurements for the study area were not available. According to rough comparisons with aggregate district data for the year 2007, the model seems to overestimate participation rates. This bias is in line with our expectations, since our decision model assessed participation only based on short-term profitability of the measure itself and did not consider other grassland conservation support outside the MEKA scheme (e.g. individual tendered contracts), transaction costs, the reluctance of farmers to commit for the required 5 years (Mettepenningen et al., 2013), or potential incongruence with farmer values (Burton et al., 2008; Burton and Schwarz, 2013). Incorporating these potential determinants of MEKA participation in the model will be an important next step to further increase the reliability of the simulation analysis.

It should not be forgotten either that the hay and grass silage yields and the dedication of grassland area to measure B4 was based only on the management decision of the agent, while natural conditions affecting grass yields and species diversity were not considered due to lack of data. Parts of the grassland in the study area may not support two or more cuts per year, even under the best management. Given the important share of grass silage in the biogas feedstock, this may also affect investments in biogas plants and the estimated effects on land shadow prices.

As a consequence, the simulated effects should not be interpreted as precise forecasts of policy effects on local level. Nevertheless, they highlight the general patterns and potential magnitudes of interaction between the two groups of policy measures and provide a sound basis upon which to refine future analysis.

Conclusions

Using a farm-level model run for every full-time farm in our study area, we simulated interactions and potential conflicts between different environmental policy schemes. Our simulation approach improved on previous research by modeling investment and participation decisions from the perspective of individual farmers, while capturing the full heterogeneity of farms in our study area. In contrast to many other policy simulation studies, our

modeling approach allowed for a flexible choice of feedstock mixture and plant sizes, and an assessment of the structural and distributional consequences of policies.

Our simulation results suggest that the effect of biogas support on MEKA participation and land use is potentially very large. Whether the latest EEG revision actually reduces the degree of 'maizification' and grassland intensification depends on the local market for biogas excess heat. In any case, any reduction in maize area would probably be achieved by a considerable reduction of the biogas production potential ("output effect"), and not by encouraging less maize-intensive feedstock mixes ("substitution effect"). The latest EEG revision consequently does not resolve the conflicts between policy objectives, but shifts priorities from the expansion of renewable energy toward environmental concerns.

Our simulation model provides a sound basis for policy analysis, helping to better coordinate policy schemes in the future and improve the design of complementary, rather than conflicting, policy schemes. To generate more reliable quantitative estimates, it is still necessary to improve our empirical data base and to capture farmer cooperation and farmer participation in agri-environmental policy schemes. With respect to the latter, research needs to focus specifically on transaction costs, the influence of the required five year commitment to the MEKA scheme, and the influence of farmer attitudes toward agri-environmental policy measures. More fine-grained spatial information on natural production and conservation potential will also need to be incorporated into the model. Simulation of biogas investments can be improved by incorporating more sophisticated agent investment rules that, for example, consider risk behavior and the optimal timing of investments (e.g. option value theory, Anderson and Weersink, 2014). Further, the assessment would benefit from advances in our ability to model locally restricted demand for excess heat, inter-farm cooperation and feedstock trade. In-depth empirical research and theory development will be necessary to advance on these issues. The implementation of the farm-level setup in MPMAS provides the basis for its extension to an agent-based model that then takes these farmer interactions into account (see e.g. Nolan et al., 2009; Berger, 2001; Schreinemachers et al., 2007, 2009; Schreinemachers and Berger, 2011; Quang et al., 2014).

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Appendix A. Details on the farm model implementation.

The farm production and investment decision problem is formulated as a mixed integer programming (MIP) problem of the form:

$$\max! \quad \sum_i (c_i x_i) + \sum_j (c_j z_j)$$

$$\text{s.t.} \quad \sum_i (a_{ik} x_i) + \sum_j (a_{jk} z_j) \le b_k \quad \forall k$$

In the following description of the problem, x generally denotes decision variables, z denotes integer decision variables, a coefficients of decision variables in constraints, b capacities (right-hand sides) of constraints and c objective function coefficients of decision variables. M as a coefficient denotes infinitely high values to allow implementing yes-or-no switches in the model.

The complete MIP matrix comprises around 6900 variables in about 3800 equations. In the following, we will concentrate on describing the equations most relevant to the present article, namely those involved in the representation of biogas production and the EEG and MEKA restriction. A full model description including all equations can be found in the model documentation (Troost, 2014) that is available at https://mp-mas.uni-hohenheim.de/documentation.

A.1. Biogas production

To be able to reflect economies of size in the construction of biogas plants, biogas investments are represented by a size-independent basic investment decision variable $z^{i\alpha Ue}$ and the size-determining decision variable $x^{i\beta Ue}$. The investment decision is formulated for an average year in the near future. Investment costs for biogas plants are consequently annualized assuming an interest rate of 6% and enter the decision problem as objective function coefficients ($c^{i\alpha Ue}$ and $c^{i\beta Ue}$).

$$c^{i\beta Ue} = -\left(2459 \times 0.06 \times \frac{(1.06)^{\lambda}}{(1.06)^{\lambda} - 1}\right) \tag{A.1}$$

$$c^{i\alpha Ue} = -\left(394,249 \times 0.06 \times \frac{(1.06)^{\lambda}}{(1.06)^{\lambda} - 1}\right) \tag{A.2}$$

We generally assumed a lifetime (λ) of 20 years for biogas plants following KTBL (2010). In the framework of our uncertainty analysis, however, we also tested settings where we reduced λ to the expected remaining lifetime of the farm if that was lower than 20 years. Depending on the setting, the expected remaining farm life is the remaining time until the current household head turns 65 or the time until the potential successor will turn 65 (see Appendix B).

Maize, wheat and grass silage as well as manure can be used in fermenters to produce biogas, which is then transformed to heat and electricity in generators. The production of biogas electricity from specific goods (g) is represented by the decision variables x_g^{uG}. Electricity yields a_g^{uG} are specific to the feedstock used (see Table 1). Production of biogas from a certain feedstock is constrained by production of this feedstock through own crop (x^L) or animal (x^A) production (purchase of feedstock x^{bG} was originally contained in the model, but discarded in calibration).

$$x_g^{uG} - \sum_l (a_{l,g}^{LG} x_l^L) - \sum_a (a_a^{AG} x_a^A) \le 0 \quad \forall g, \tag{A.3}$$

Biogas production requires maintenance of the biogas plant (x^{mUe}) with size-dependent monetary maintenance cost ($c^{\beta mUe}$).

$$\begin{array}{llllll}
\sum_g (a_g^{GUe} x_g^{uG}) & -x^{\beta mUe} & & & & \le & 0 \\
 & x^{\beta mUe} & & & -x^{i\beta Ue} & = & b^{\beta Ue} \\
 & x^{\beta mUe} & -Mz^{\alpha mUe} & & & \le & 0 \\
 & & z^{\alpha mUe} & -z^{i\alpha Ue} & & = & b^{\alpha Ue} \\
 & & & -Mz^{i\alpha Ue} & +x^{i\beta Ue} & \le & 0
\end{array} \tag{A.4}$$

(Note: previously installed capacities $b^{\alpha Ue}$, $b^{\beta Ue}$ are zero in the present analysis.)

Size-independent labor demand for maintenance ($a^{H\alpha mUe}$) and feedstock-specific labor demand for biogas production (a_g^{uGH}) is assumed to occur every day as the biogas plant is run throughout the whole year. In the model, the labor capacity of the household (consisting of the number of household members working on the farm, x^H, and hired permanent employees, x^{bpH}) can be either reserved for the seasonal field work (x^{tHw}, see Troost and Berger, 2014) or for constant daily tasks (x^{tHd}) occurring in animal and biogas production.

$$x^{tHw} + x^{tHd} - x^{bpH} - x^H \leq 0 \tag{A.5}$$

Labor reserved for constant daily labor is multiplied by the assumed amount of daily working hours ($a^{Hd} = 9$), and is available for animal production and related activities as well as biogas plant maintenance and production.

$$-a^{Hd}x^{tHd} + \sum_a (a_a^{AH}x_a^A) + \ldots + \sum_g (a_g^{uGH}x_g^{uG}) + a^{H\alpha mUe}z^{\alpha mUe} \leq 0 \tag{A.6}$$

Biogas production (x_g^{uG}) further requires process electricity (x^{bGp}), which amounts to 7% of electric energy produced (KTBL, 2010) and has to be bought at standard electricity prices (c^{bGp}).

$$0.07\sum_g (a_g^{uG}x_g^{uG}) - x^{bGp} \leq 0 \tag{A.7}$$

Special attention was paid to the manure balance as manure is both an input and a product of biogas production. The manure balance links land use, animal production and biogas production. Manure produced by animals can be either used in a biogas plant ($x_{g_o}^{uG}$) or directly spread on the field or grassland ($x_{g_o}^{tGo}$).

$$x_{g_o}^{uG} + x_{g_o}^{tGo} - \sum_a (a_{a,g_o}^{AGo}x_a^A) \leq 0 \quad \forall g_o \tag{A.8}$$

Currently, we distinguish only two types of manure ($g_o \in Go$), cattle and pig manure. For simplification, we assume that the residue from biogas production from manure is equivalent to the manure input with respect to fertilization. According to expert opinion this seems justified as an approximation at least with respect to total nitrogen amounts, the only nutrient explicitly considered in the crop growth model used to calculate crop yields in the model. Residue from biogas production with silage feedstock ($g_b \notin Go$) is transformed into pig and cattle manure equivalents (a_{g_o,g_p}^{uGGo}) based on nitrogen content, so that the balance for organic fertilization can be formulated as:

$$\sum_l (a_{l,g_o}^{LGo}x_l^L) - x_{g_o}^{uG} - \sum_{g_b \notin Go} (a_{g_o,g_b}^{uGGo}x_{g_b}^{uG}) - x_{g_o}^{tGo} \leq 0 \quad \forall g_o \tag{A.9}$$

At the same time, all the manure produced also has to be spread on the field. For computational reasons, we allow a certain slack here in order to give some flexibility to the MIP solver; the corresponding coefficient ζ_{manure} is part of the uncertainty analysis.

$$-\zeta_{\text{manure}}\sum_l (a_{l,g_o}^{LGo}x_l^L) + \sum_a (a_{a,g_o}^{AGo}x_a^A) + \sum_{g_b \notin Go} (a_{g_o,g_b}^{uGGo}x_{g_b}^{uG}) \leq 0 \quad \forall g_o \tag{A.10}$$

A.2. The EEG in the model

The EEG guarantees a price to the electricity producer for 20 years from the start of electricity production. The individual price paid for a kWh of a certain biogas plant depends on the year the plant first entered into production ($y_y \in Yy$) and is tiered by volume ($y_u \in Yu$).

In the model implementation of *EEG 2009*, an individual decision variable x_{y_u,y_y}^{sYyYu} reflects the sale of a quantity of electrical energy for the price c^{sYyYu} valid under tier $y_u \in Yu$ for plants established in year $y_y \in Yy$. In the simulations for this article we generally assume $y_y = 2012$ (see Table 2 for corresponding prices c^{sYyYu}). Agents in the model who are not not willing to comply with the EEG requirements for receiving the guaranteed prices can still sell the electricity at market prices (x^{sGe}).

$$x^{sGe} + \sum_{y_u,y_y} x_{y_u,y_y}^{sYyYu} - \sum_g (a_g^{uG}x_g^{uG}) \leq 0. \tag{A.11}$$

Remuneration of biogas plants under EEG requires registering the year (x^{iYy}) the biogas plant enters production establishing the contracted capacity (b_{Yy}) that allow receiving the corresponding guaranteed price (for this analysis $b_{y_y}^{Yy} = 0\ \forall y_y$).

$$\sum_{y_u,y_y} x_{y_u,y_y}^{sYyYu} - x_{y_y}^{iYy} \leq b_{y_y}^{Yy} \quad \forall\ y_y \tag{A.12}$$

$$x_{y_y}^{iYy} - x^{i\beta Ue} \leq 0 \quad \text{for} \quad y_y = 2012 \tag{A.13}$$

Remuneration under each tier is constrained by the maximum volume allowed under the tier ($b_{y_u}^{YyYu}$).

$$x_{y_u,y_y}^{sYyYu} \leq b_{y_u}^{Yu} \quad \forall (y_u, y_y) \tag{A.14}$$

Since all feedstock categories considered in our model fulfill the requirements for the EEG 2004 and 2009 NaWaRo bonus, it is automatically included in c^{sYyYu}. The manure bonus of EEG 2009 requires a minimum of 30% manure ($g \in Go$) in the total mass of the feedstock. This condition is implemented using a binary decision of either accepting the condition and receiving the bonus (z^{yuo}) or relaxing the condition on minimum manure use (z^{nuo}) and forgo the bonus.

$$\begin{aligned}
&\sum_{y_u,y_y} x_{y_u,y_y}^{osYyYu} - \sum_{g \in Go} (a_g^{uG}x_g^{uG}) && \leq 0 \\
&\sum_{y_u,y_y} x_{y_u,y_y}^{osYyYu} - Mz^{yuo} && \leq 0 \\
&z^{yuo} + z^{nuo} && \leq 1 \\
&x_{y_u,y_y}^{osYyYu} && \leq b_{y_u,y_y}^{oYyYu} \quad \forall (y_u, y_y)
\end{aligned} \tag{A.15}$$

Apart from the electricity also the heat produced during the burning of biogas (a_g^{uGh}) can potentially be sold (x^{suh}) or used as input for animal production (a_{heat}^{AG}) on the farm (replacing heat or gas purchases, x_{heat}^{bG}). The combined use of heat and electricity is rewarded with an additional CHP bonus under EEG 2004 and 2009 (x^{sYuh}).

$$\begin{aligned}
&-\sum_{g \in Gb} \left(a_g^{uGh}x_g^{uG}\right) + x^{tuh} && \leq 0 \\
&x^{suh} - x^{tuh} + x^{tuh2} && \leq 0 \\
&-x_{heat}^{bG} + \sum_a \left(a_{\text{heat}}^{AG}x^A\right) - x^{tuh2} && \leq 0 \\
&x^{sYuh} - x^{tuh} && \leq 0
\end{aligned} \tag{A.16}$$

Both, manure and CHP bonus can only be rewarded for electricity for which also the base rate is awarded:

$$\begin{aligned} \sum_{y_u,y_y} x^{osYyYu}_{y_u,y_y} \quad & -\sum_{y_u,y_y} x^{sYyYu}_{y_u,y_y} \leq 0 \\ x^{sYuh} \quad & -\sum_{y_u,y_y} x^{sYyYu}_{y_u,y_y} \leq 0 \end{aligned} \tag{A.17}$$

The *EEG2012* replaces the old system of base price and boni by introducing two remuneration classes for biogas feedstock. The remuneration is granted according to the share of the feedstock classes in the total methane produced. As the remuneration remains tiered (Yu), this introduces a quadratic relationship into the constraints, which has to be resolved using discretization in our mixed integer linear model. We defined remuneration activities (Yz) with fixed relationships between the two remuneration classes ranging from 100% remuneration class I to 100% remuneration class II in steps of 10%. Except for the extremes, we introduced two activities at each step, one ($x^{slYyYuYz}$) serving as the lower bound of a 10% interval and the other as the upper bound ($x^{suYyYuYz}$).

We further defined mutually exclusive binary activities ($z^{ynoYyYz}$), which make sure the boundary activities of only one interval within a tier can be used. In this way, we make sure that the relationship between the remuneration classes is (at least approximately) equal in all tiers. Otherwise the optimization might lead to the remuneration of electricity of one class in the lower tier and of the other one in a higher tier. (The relationship between rewards granted for each remuneration class is not the same between the tiers.)

$$\begin{aligned} x^{slYyYuYz}_{y_u,y_y,y_z+1} \quad + x^{suYyYuYz}_{y_u,y_y,y_z} \quad & -a^{Yu} z^{ynoYyYz}_{y_y,y_z} \leq 0 \quad \forall y_z, y_u, y_y \\ & \sum_{y_z} (z^{ynoYyYz}_{y_y,y_z}) \leq 1 \quad \forall y_y \end{aligned} \tag{A.18}$$

The EEG 2012 further restricts the share of maize in the total feedstock mass to 60%,

$$\begin{aligned} \sum_{y_u,y_y,y_z} (x^{slYyYuYz}_{y_u,y_y,y_z+1} + x^{suYyYuYz}_{y_u,y_y,y_z}) \quad & -Mz^{y12m} \leq 0 \\ z^{y12m} \quad & +z^{n12m} \leq 1 \end{aligned} \tag{A.19}$$

and requires the combined use of at least 60% of the heat for plants, whose feedstock consists of less than 60% manure. A special unified premium (x^{sYx}) is granted for small plants up to 75 kW that use manure for more than 80% of the electricity production. Together with the manure bonus of EEG 2009, these are combined into a mutually exclusive set of reward options in the model using binary activities,

$$z^{yYx} + z^{y60o} + z^{yuo} + z^{nuo} \leq 1 \tag{A.20}$$

which are used to apply different manure share requirements,

$$\begin{aligned} \sum_g x^{uG}_g \quad & -x^{tYx} \quad -x^{tu60o} \quad -x^{tuGo} \quad -Mz^{nuo} \leq 0 \\ -\sum_{g\in Go} (x^{uG}_g) \quad & +0.8x^{tYx} \quad +0.6x^{tu60o} \quad +0.3x^{tuGo} \leq 0 \end{aligned} \tag{A.21}$$

with

$$\begin{aligned} x^{tu60o} \quad & -Mz^{y60o} \leq 0 \\ x^{tuGo} \quad & -Mz^{yuo} \leq 0 \end{aligned} \tag{A.22}$$

and then allow the use of the respective schemes:

$$x^{sYx} - Mz^{yYx} \leq 0 \tag{A.23}$$

$$a^{rCHP} \sum_{y_u,y_y,y_z} (x^{slYyYuYz}_{y_u,y_y,y_z+1} + x^{suYyYuYz}_{y_u,y_y,y_z}) - Mz^{y60o} \leq 0 \tag{A.24}$$

In our simulations, we only consider the two extreme scenarios that either all or no agents can use all of the available heat. The requirement to use the heat is therefore not explicitly implemented in the model. Under the assumption that all agents have the potential of external heat use, the coefficient a^{rCHP} is set to zero as the condition will be fulfilled per se. In the other case, the coefficient a^{rCHP} is set to one and no biogas plant with less than 60% of manure can be rewarded according to EEG 2012.

Of course, the total biogas electricity sold cannot surpass the quantity produced:

$$\begin{aligned} & x^{sYx} + x^{sGe} + \sum_{y_u,y_y,y_z} (x^{slYyYuYz}_{y_u,y_y,y_z+1} + x^{suYyYuYz}_{y_u,y_y,y_z}) \\ & -\sum_{g\in Gb} (a^{uG}_g x^{uG}_g) \leq 0 \end{aligned}$$

As before, remuneration under EEG 2012 is subject to the establishment of an EEG contract.

$$\begin{aligned} x^{sYx} \quad + \sum_{y_u,y_y,y_z} (x^{slYyYuYz}_{y_u,y_y,y_z+1} + x^{suYyYuYz}_{y_u,y_y,y_z}) \quad & -x^{iYy}_{yy} \leq b^{Yy}_{yy} \quad \forall y_y \\ x^{iYy}_{yy} \quad & -x^{i\beta Ue} \leq 0 \quad for \quad y_y = 2012 \end{aligned} \tag{A.25}$$

A.3. MEKA III

For each of the four MEKA measures ($y_m \in Ym$) a certain number of points ($a^{Ym}_{y_m}$) is awarded for each unit ($x^{Ym}_{y_m}$, e.g. ha, animal, farm) registered for participation. For each point received (x^{sYm}), the agent is rewarded with $c^{sYm} = 10$ Euro under MEKA III regulations.

$$x^{sYm} - \sum_{y_m} (a^{Ym}_{y_m} x^{Ym}_{y_m}) \leq 0 \tag{A.26}$$

A minimum amount to be rewarded of 250 Euro is required for participation and a maximum of 40,000 Euro can be awarded per agent.

$$\begin{aligned} c^{sYm} x^{sYm} \quad & \leq 40,000 \\ x^{sYm} \quad & -Mz^{ylYm} \leq 0 \\ -c^{sYm} x^{sYm} \quad & +250 z^{ylYm} \leq 0 \end{aligned} \tag{A.27}$$

The implementation of measure *A2 (Diversification of crop rotation)* requires the inclusion of several binary integer variables: two variables to represent the decision whether to participate (z^{yYm}_{3A2}) or not (z^{nYm}_{3A2}), which are of course mutually exclusive.

$$z^{yYm}_{3A2} + z^{nYm}_{3A2} \leq 1 \tag{A.28}$$

Then for each crop group (Jym) potentially included in the agent crop rotation and counted for diversification, two binary integer

variables indicate whether it has been included (z_{jym}^{yJym}) or not (z_{jym}^{nJym}). The condition of requiring at least four crops with a minimum share of 15% is enforced in the model by the following system of equations (note: x_s^{Sr} is a crop rotation variable that sums up all arable land):

$$\begin{aligned}
4z_{3A2}^{yYm} - \sum_{jym} z_{jym}^{yJym} &\leq 0 \\
z_{jym}^{yJym} + z_{jym}^{nJym} &\leq 1 \quad \forall j_{ym} \\
\sum_s x_s^{Sr} - x_{3A2}^{t1Ym} - x_{3A2}^{t2Ym} &\leq 0 \\
-Mz_{jym}^{nJym} + 0.15x_{3A2}^{t1Ym} + 0.15x_{3A2}^{t2Ym} - \sum_l (1_{l,jym}^{LJym} x_l^L) &\leq 0 \quad \forall j_{ym}
\end{aligned} \tag{A.29}$$

Fallow can be counted as a crop to fulfill diversification requirements, but no points are awarded for fallow areas. Two more variables are needed in the model to distinguish between fallow area (x_{3A2}^{t1Ym}) and non-fallow area (x_{3A2}^{t2Ym}). According to MEKA regulations, only the later can be counted to achieve the points:

$$\begin{aligned}
x^{sYm} - 1x_{3A2}^{t2Ym} &\leq 0 \\
-Mz_{3A2}^{yYm} + x_{3A2}^{t1Ym} + x_{3A2}^{t2Ym} &\leq 0 \\
x_{3A2}^{t1Ym} - \sum_{l \in Loil} x_l^L &\leq 0 \\
x_{3A2}^{t2Ym} - \sum_{l \notin Loil, Lgg} x_l^L &\leq 0
\end{aligned} \tag{A.30}$$

Further, the restriction on maize cultivation is implemented as follows:

$$\sum_{l \in Lmai} x_l^L - 0.4x_{3A2}^{t1Ym} - 0.4x_{3A2}^{t2Ym} - Mz_{3A2}^{nYm} \leq 0 \tag{A.31}$$

As in reality, agent participation in the *extensive grassland measures B1*(z_{3B1}^{yYm}) and *B2* (z_{3B2}^{yYm}) is mutually exclusive.

$$z_{3B1}^{yYm} + z_{3B2}^{yYm} + z_{3B}^{nYm} \leq 1 \tag{A.32}$$

The restriction on the animal-to-land ratio (< 2 LSU/ha agricultural area for B1 and < 1.4 LSUA/ha AA and 0.3–1.4 gLSU/ha fodder area for B2) is implemented in the model using different calculation activities (x^{clu}, x^{crlu}).

For the LSU/AA ratio:

$$\begin{aligned}
\sum_a (a_a^{Alu} x_a^A) - 2.0x_{3B1}^{clu} - 1.4z_{3B2}^{clu} - Mz_{3B}^{nYm} &\leq 0 \\
x_{3B1}^{clu} + x_{3B2}^{clu} - \sum_l x_l^L &\leq 0 \\
x_{3B1}^{clu} - Mz_{3B1}^{yYm} &\leq 0
\end{aligned} \tag{A.33}$$

For the gLSU/MF ratio:

$$\begin{aligned}
\sum_a (a_a^{Alu} x_a^A) - 1.4x_{3B2}^{crlu} - Mx_{n3B2}^{crlu} &\leq 0 \\
-\sum_a (a_a^{Alu} x_a^A) + 0.3x_{3B2}^{crlu} &\leq 0 \\
x_{3B2}^{crlu} + x_{n3B2}^{crlu} - \sum_{l \in Lmf} x_l^L &= 0 \\
x_{n3B2}^{crlu} - Mz_{3B1}^{yYm} - Mz_{3B}^{nYm} &\leq 0
\end{aligned} \tag{A.34}$$

Receiving points requires fulfillment of the conditions and is restricted by the available grassland area, and in the case of B1 by the additional condition of cutting 5% of the area the first time after the fifteenth of July.

$$\begin{aligned}
x_{3B1}^{Ym} + x_{3B2}^{Ym} - \sum_{l \in Lgg} x_l^L &\leq 0 \\
0.05x_{3B1}^{Ym} - \sum_{l \in Lb4} x_l^L &\leq 0 \\
x_{3B1}^{Ym} - Mx_{3B1}^{yYm} &\leq 0 \\
x_{3B2}^{Ym} - Mx_{3B2}^{yYm} &\leq 0 \\
-x_{3B1}^{Ym} + x_{3B1}^{yYm} &\leq 0 \\
-x_{3B2}^{Ym} + x_{3B2}^{yYm} &\leq 0
\end{aligned} \tag{A.35}$$

As mentioned above we assume in the model that grassland activities with late cuts (*Lb4*) fulfill the required species mix for *measure B4*.

$$x_{3B4}^{Ym} - \sum_{l \in Lb4} (x_l^L) \leq 0 \tag{A.36}$$

Appendix B. Model uncertainty

Table 7 lists the 19 parameters of the MPMAS Central Swabian Jura model that were identified as uncertain after calibration by Troost and Berger (2014). After an elementary effects screening (Campolongo et al., 2007) with 1200 simulation runs to identify the parameters with the highest influence on installed biogas capacity, maize areas, land use and MEKA participation, we retained 14 parameters for the experimental design used in the main part of

Table 7
Parameter settings tested during the calibration and validation experiments.

Parameter group	Parameter	Range	Fixed at
Initial agent population	***population***	Three asset distributions	
	birth_factor_past	[1; 1.05]	
	potsuc_prob_male	[0.5; 1]	
Yields	***maize_yc***	[0.8; 0.9]	
	wheat_normal	[1; 1.1]	
	wps	Yes/no	Yes
	wps_coef	[1;1.3]	1.15
Crop rotation	*maize_on_maize*	0, 1/2, 1	1/2
	maizerotlimit	[0.4;0.6]	
Field working days	***clregion***	4, 5	
Contracted field work	*workforhirecoef*	[0; 1]	0.5
	proptohire	[0.5; 2]	
Cattle feeding	***freshgrasslabor***	[1; 3]	
	freshgrassloss	[0; 0.2]	0.1
Markets	***biertreber***	Yes/no	
	kwkyno	Yes/no	
Manure	***high_manure_maize***	Yes/no	
	manure	[1; 1.5]	
Farm household	***ihorizon_type***	4 different versions	

the analysis. These are printed in boldface in the table. The five parameters that showed little influence were fixed at the value shown in the third column of the table.

The first three parameters control the characteristics of the input agent population. The first one determines which of the three sampled agent populations were used. *birth_factor_past* scales the fertility assumed when determining the initial agent household compositions (considering that birth rates in the past and in rural areas were probably higher than the German average of the last decade). *potsuc_prob_male* is the probability that a male descendant is interested to pursue a career in farming and thus is considered a potential successor of the current farm manager.

Parameters related to crop yields include a scaling factor for wheat (*wheat_normal*), a scaling factor for silage maize yields (*maize_yc*) to reflect the uncertainty of maize production in the study region, and two factors which include or exclude the production of whole-plant silage (*wps*) and scale whole-plant silage yields (*wps_coef*) as we consider this an innovation and we have no data on the diffusion of this technology and little information on crop yields.

Two parameters affect the potential maize area of an agent: *maize_on_maize* controls the number of years that maize can be grown after itself, and *maizerotlimit* constitutes the upper limit for the total share of maize in the crop rotation.

Parameters related to field work include the KTBL climate region for estimating the available days for field work (*clregion*). Further, the *workforhirecoef* scales the price for contracted field work between the maximum and the minimum of the range given in KTBL (2010), while the *proptohire* coefficient scales the availability of hired field work per hour with suitable weather (see Troost and Berger, 2014).

The *freshgrasslabor* coefficient scales the amount of labor necessary for feeding freshly cut grass and the *freshgrassloss* coefficient indicates the share of corresponding harvest losses. The *biertreber* parameter controls whether brewery by-products are generally available as fodder. The *kwkyno* parameter controls whether excess process heat can be sold on local markets.

Two parameters are related to the maximum amount of manure that can be applied to a crop. The production activities that consider manure use, assume a standard amount of manure use, which effectively creates an upper limit of manure application to each crop. The *manure* parameter scales this upper limit on manure use of all production activities in order to test whether the assumed standard amounts may be too low. The *high_manure_maize* is specific to silage maize production. It controls the inclusion of specific silage maize production activities, which assume a manure amount of 30 m^3 instead of the standard 20 m^3 (with the complementing mineral fertilization reduced).

Last, the *ihorizon_type* represents four different implementations of the influence of farm household composition on the production decisions of the farm: In the simplest version, the investment horizon (λ) is independent of the farm manager's age and the farm manager derives no utility from employing potential successors. In the second version, the investment horizon remains independent of the farm manager's age, but the farm manager derives utility from employing potential successors (see Troost and Berger, 2014). In the third version, the investment horizon depends only on the age of the current household head, while in the fourth version it depends on the age of a potential successor if available.

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