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Biogas production in the light of the German Fertilization Ordinance: An economic and environmental assessment at farm and regional scale

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Abstract

In Germany, the expansion of biogas plants is fostered by the Renewable Energy Sources Act to support the energy transition. Beneficial aspects of biogas such as providing flexible renewable energy and generating additional income for farmers are contrasted by its high costs and negative environmental impacts. Due to reduced subsidies the expansion came almost to a halt in 2014, however, negative environmental impacts of existing plants are still prevalent. The associated downsides include the effects of maize monocultures and additional nutrient pressure from the by-product biogas digestate on the quality of water bodies. The primary regulation to limit nutrient losses to water bodies is the German Fertilization Ordinance (FO), which was revised in 2017 and 2020 imposing considerable stricter nutrient application thresholds such as lower phosphate (P_2O_5) balance thresholds and a modified accounting for nitrogen (N) from plant-based biogas digestate. Biogas plants and livestock farmers have several strategies to comply with the FO and to mitigate N and P_2O_5 losses, with selling the excess nutrients on the organic fertilizer market being the most prominent one. This thesis aims to assess the policies at farm and regional level which intend to alleviate the negative environmental impacts of the increased biogas production. The focus in this thesis is on the German state of North Rhine-Westphalia (NRW).

The dissertation entails three studies which all differ in methodological approach and assessed policy measures. The first study extends a bio-economic farm model with a biogas plant and evaluates a subsidy which aims at the production of flexible renewable energy and input reduction of existing biogas plants. Thereby, it explores an option to reduce the negative impact associated with biogas production. In the second study a spatial price equilibrium model is developed to depict the organic fertilizer market and applied to selected measures of the revised FO 2017 and 2020. To improve the policy assessment, a bi-level calibration is established, and the results are compared to those of a non-calibrated model which are most common in the literature on organic fertilizer markets. The third study extends and applies an agent-based model with an organic fertilizer market. The inclusion of a meta-model allows a comprehensive assessment of the FO 2017 on organic fertilizer transport for the heterogenous farm population of NRW.

Changing the operation mode and reducing the input in biogas plants can be used to produce flexible energy and therefore contributes to the energy transition while lowering the quantity of biogas digestate. However, the remuneration costs for electricity production are even with moderate input reduction extremely high and difficult to justify given that electricity from biogas is the costliest among the renewable energies. The more common compliance strategy, exporting excess biogas digestate or other organic fertilizer, is going to increase in quantity and distance as a consequence of the revised FO 2017 and 2020. Next to the accounting of plant-based biogas digestate in the N application limit, the P_2O_5 balance threshold leads to an expansion of transports especially for pig fattening farms with high stocking densities. The increase in transport distance and quantity can be observed from counties with a high number of biogas plants and livestock into both adjacent counties and far-off counties within NRW. The associated nutrient flows show that transports can increase N quantities in regions with already high groundwater pollution levels. Policymakers have to consider implementing measures to prevent further deterioration of ground water bodies in those regions.

Zusammenfassung

Ein zentrales Element zur Umsetzung der Energiewende in Deutschland ist das Erneuerbare-Energien-Gesetz, welches den Ausbau von Biogas und anderen erneuerbaren Energien fördert. Den positiven Aspekten von Biogas, wie der Bereitstellung von flexibler erneuerbarer Energie und der Generierung von zusätzlichem Einkommen für Landwirte, stehen die hohen Kosten und negativen Umweltauswirkungen gegenüber. Obwohl reduzierte Subventionen den Ausbau ab 2014 verlangsamt haben, wirken sich bestehende Anlagen noch heute negativ auf die Umwelt aus. Sie führen beispielsweise zum Anbau von Maismonokulturen und zusätzlicher Belastung von Gewässern durch die Nährstoffe aus Biogasgärresten. Die zentrale Regulierung zur Begrenzung der Nährstoffverluste in Grund- und Oberflächengewässern ist die Düngeverordnung (DüV), die 2017 und 2020 überarbeitet wurde und deutlich strengere Grenzwerte für die Nährstoffausbringung vorschreibt, wie z. B. niedrigere Grenzwerte für die Phosphatbilanz (P_2O_5) und die Anrechnung von Stickstoff (N) aus pflanzlichen Biogasgärresten. Biogasanlagen und Tierhalter haben zahlreiche Strategien, um die DüV einzuhalten und N- und P_2O_5-Verluste zu mindern. Die Abgabge von überschüssigen organischen Dünger ist dabei eine weit verbreitete Anpassungsstrategie. Diese Dissertation untersucht die politischen Maßnahmen zur Minderung der negativen Umwelatauswirkungen einer verstärkten Biogasproduktion auf betrieblicher und regionaler Ebene, wobei der Schwerpunkt auf dem deutschen Bundesland Nordrhein-Westfalen (NRW) liegt.

Die Dissertation umfasst drei Studien, die sich im methodischen Ansatz und den bewerteten politischen Maßnahmen unterscheiden. Die erste Studie erweitert ein bioökonomisches Betriebsmodell um eine Biogasanlage und evaluiert eine Förderung, die auf die Produktion flexibler erneuerbarer Energie und die Inputreduktion bestehender Biogasanlagen abzielt. Damit wird eine Möglichkeit untersucht, die mit der Biogasproduktion verbundenen negativen Umweltauswirkungen zu reduzieren. In der zweiten Studie wird ein räumliches Gleichgewichtsmodell, das den Markt für organische Düngemittel abbildet, erstellt und auf ausgewählte Maßnahmen der überarbeiteten DüV 2017 und 2020 angewendet. Dazu wird ein Bi-Level Kalibrierungsverfahren entwickelt und auf die Nährstofftransportdaten von NRW angewandt. In der Literatur zu organischen Düngermärkten sind bisher unkalibrierte Modelle vorherrschend. Um diese Lücke zu schließen werden im Rahmen der Studie die Vorteile der Kalibrierung aufgezeigt in dem die Kalibrierungsergebnisse und Simulationsergebnisse eines nicht kalibrierten Modells verglichen

werden. Die dritte Studie erweitert ein agentenbasiertes Modell um einen organischen Düngermarkt. Die Verwendung eines Metamodells ermöglicht dabei eine umfassende Bewertung der DüV 2017 mit Fokus auf die organische Düngermitteltransporte zwischen landwirtschaftlichen Betrieben in NRW.

Die Reduzierung des Inputs in Biogasanlagen kann zur flexiblen Energieerzeugung genutzt werden und trägt damit zur Energiewende bei gleichzeitiger Senkung der Biogasgärrestmenge bei. Allerdings sind die Vergütungskosten für die Stromerzeugung selbst bei moderater Einsatzreduzierung sehr hoch und angesichts der Tatsache, dass Strom aus Biogas der teuerste unter den erneuerbaren Energien ist, schwer zu rechtfertigen. Die gängigere Anpassungsstrategie, die Abgabe von überschüssigen Biogasgärresten oder anderen organischen Düngemitteln, wird als Folge der überarbeiteten DüV 2017 und 2020 in Menge und Entfernung zunehmen. Neben der Anrechnung von pflanzlichen Biogasgärresten auf die N-Ausbringungsgrenze, führt die Limiterung des P_2O_5-Überschuss insbesondere bei Schweinemastbetrieben mit hohen Besatzdichten zu einer Ausweitung der Transporte. Die Zunahme der Transportmenge ist aus Kreisen mit einer hohen Anzahl an Biogasanlagen und Viehbeständen sowohl in angrenzende Kreise als auch in weit entfernte Kreise innerhalb NRWs zu beobachten. Die dazugehörigen Nährstoffflüsse zeigen, dass die Transporte die N-Mengen in Regionen mit bereits starken Belastungen im Grundwasser erhöhen können. Die Politik muss Maßnahmen in Betracht ziehen, um eine weitere Verschlechterung der Grundwasserkörper durch zusätzliche Nährstoffimporte in diesen Regionen zu verhindern.

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Abbreviations

ABM	Agent-based model
BEFM	Bio-economic farm level model
BMEL	Bundesministerium für Ernährung und Landwirtschaft
BMELV	Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz
BMU	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit
BMWI	Bundesministerium für Wirtschaft und Energie
CHP-bonus	Combined-Heat-Power-bonus
CLC	CORINE land cover
CORINE	Coordination of information on the environment
EEA	European Environment Agency
EU	European Union
FIT	Feed-in tariff
FO	Fertilization Ordinance
FSS	Farm Structural Survey
GAMS	General Algebraic Modeling System
GHG	Greenhouse gas
GIS	Geographic Information Systems
HPD	Highest-posterior density
KKT	Karush-Kuhn-Tucker
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. Darmstadt, Germany
LWK	Landwirtschaftskammer
MAC	Manure application contract
MAPE	Mean absolute percentage error
MILP	Mixed integer linear programming
MP	Mathematical programming
MULNV	Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia
MW	Megawatt

N	Nitrogen
ND	Nitrates Directive
NLP	Non-linear programming
NO_3^-	Nitrate
NPH	Nitrate pollution hotspot
NPV	Net present value
NRW	North Rhine Westphalia
P	Phosphorus
P_2O_5	Phosphate
RES	Renewable Energy Sources Act
SPE	Spatial price equilibrium
USL	Umweltverträgliche und Standortgerechte Landwirtschaft
UUA	Utilized agricultural area
WFD	Water Framework Directive

Chapter 1

Introduction

1.1 Background

Biogas production describes the process in which organic inputs are fermented to create a gas mixture used to generate energy in the form of electricity and heat. In Germany the expansion of biogas and other renewable energies such as wind and solar power is fostered by the Renewable Energy Sources Act (RES) ("Erneuerbare-Energien Gesetz") (BMWI 2014); a subsidy scheme which introduced renewable energy specific feed-in tariffs for electricity and heat. The RES is a pivotal part of the German energy transition ("Energiewende") which aims at a shift from a fossil fuel based to a renewable energy based economy (BMWI 2019). To stay on the trajectory of the targets set by the energy transition, the RES is amended from time to time to account for new technological developments and insights in cost efficiency and sustainability of the subsidy scheme.

Since the inception of the RES in 2000, the biogas sector has experienced a massive growth which continued during the time of the first and second amendment of the RES in 2004 and 2009, respectively. The installed electric capacity of biogas plants in Germany grew from less than 200 megawatt (MW) to almost 4000 MW in the thirteen years after the introduction of the RES (Fachverband Biogas 2020). Biogas was praised, on the one hand, as being helpful in the energy transition as it can provide electricity on demand to balance out fluctuating energy sources like wind and solar power. On the other hand, it is considered a secure income source for farmers due to its fixed premium for produced electricity for the duration of 20 years. A feature which was emphasized in the RES 2012 amendment through a special subsidy scheme for direct marketing of flexibly produced electricity (BMWI 2011).

During that time, however, the widespread instalment of biogas plants came under scrutiny, when multiple studies emerged revealing potential economic and environmental hazards linked to the expansion of the biogas (EEA 2007; Emman et al. 2014; Rauh 2010). The development of biogas production is associated with an increasing demand for its primary input, maize silage. Due to its favourable biogas yield per hectare, the area of maize silage cultivation started to rise with often monocultural structures accompanied by its negative environmental impacts such as the loss of biodiversity, increased soil erosion, and ploughing of permanent grassland (EEA 2007; Osterburg und Röder 2013). To dampen this trend, the RES 2012 amendment introduced a limit on maize silage use and implemented a remuneration structure for newly erected biogas plants that pays more for crops which are deemed to have environmentally friendly properties (BMWI 2011). Eventually, high costs of energy supply from biogas compared to other renewable energies provoked the restriction of new biogas plants in the subsequent RES 2014 and 2017 amendment. It imposed a limit of 100 MW (RES 2014) and 150 MW (RES 2017), respectively, installed electric capacity per year and introduced changes in the subsidy scheme which supported the conversion of existing biogas plants to a flexible operation mode and at the same time made small biogas plants, which use primarily manure, economically viable (BMWI 2014; Daniel-Gromke et al. 2019).

Detrimental environmental impacts were not only caused by the input side of the biogas sector but are also linked to a by-product of the biogas fermentation step. Biogas digestate, the residue of the fermentation process in the biogas production is used as organic fertilizer to provide essential nutrients for plant growth such as nitrogen (N) and phosphate (P_2O_5). However, the use of organic fertilizer is also prone to losses of these nutrients to the environment which can have hazardous effects on aquatic ecosystems (Grizetti et al. 2011), terrestrial ecosystems (Dise et al. 2011), and human health (Townsend et al. 2003). Already prior to the rise of biogas plants, the agricultural sector experienced intensification trends in livestock holdings which led to a divergence between nutrient need for plant growth and nutrient accumulation from animal manure on-farm (Naylor et al. 2005; Steinfeld et al. 2006). This problematic development was further aggravated by farm structures dominated by animal husbandry resulting in spatial concentrations of organic fertilizer and their respective nutrient losses to the environment (van Grinsven et al. 2012; Umweltbundesamt 2014). Eventually, the additional nutrients from biogas digestate exacerbated the situation, especially due to a peculiar treatment in the German fertilizer policy, the so-called Fertilization Ordinance (FO).

1.2 Problem statement

The FO is the primary agricultural and environmental policy instrument to regulate the use of organic and chemical fertilizer to limit the losses of N and P_2O_5. Based on a command-and-control approach for farms, it includes required application techniques, minimum manure storage capacities, manure application periods, and different limitations on nutrient application (BMEL 2017). The FO is the direct implementation of the European Union (EU) Nitrates Directive (ND) and contributes to the attainment of its main target, the limit of 50 mg nitrate (NO_3^-) l^{-1} as a standard of good water quality (European Council 1991). Similar to the RES, the measures in the FO have to be evaluated every four years and if necessary revised to meet the targets laid out by the ND. Despite the consistently high NO_3^- pollution levels in many groundwater bodies (BMEL und BMU 2012), the German government only initiated a revision of the FO 2007 after infringement proceedings were started by the EU-Commission in 2012 (European Commission 2016), which led to a new FO in 2017 and a further revision in 2020 (BMEL 2017, 2020). Biogas digestate had a unique accounting towards the application limit of organic N until the revised FO came into force in 2017. The FO 2007 distinguished between animal-based and plant-based sourced organic N in biogas digestate, where the former had to be accounted for in the 170 kg N ha^{-1} application limit while the latter did not. In addition, the RES amendment 2009 included a subsidy premium for a minimum use of manure in the fermentation process, which made investments in biogas plants for livestock intensive farms highly profitable (BMWI 2009). The combination of the loophole in the accounting and the construction of biogas plants linked to livestock intensive farms enabled the expansion of biogas plants in regions with already high nutrient loads stemming from animal husbandry (LWK NRW 2018).

To alleviate high nutrient loads from animal manure and biogas digestate on-farm and to fulfil the imposed requirements of the FO, exports of organic fertilizer emerged as one of the primary compliance strategies by farmers. Based on the multi-pollutant policy design of the FO, the defined measures inducing organic fertilizer exports are, however, not only limited to N but also encompass P_2O_5. The P_2O_5 balance threshold represents the most restricting measure for pig farms and biogas plants using pig manure as a co-substrate since pig manure exhibits a high P_2O_5 content (Delzeit und Kellner 2014). Even prior to the revision of the FO 2017, biogas digestate and pig manure are the two most frequently transported organic fertilizer in the German state of North-Rhine Westphalia (NRW) in 2016 (LWK NRW 2018). It is expected that the interaction of multiple more restrictive measures in the revised FO 2017, such as a reduced P_2O_5 threshold and the closure of the policy gap for biogas digestate, will have a substantial impact on the organic fertilizer market and will thus lead to increased transport quantities and distances. Early studies indicate that on-farm an increase in exports for pig farms is to be expected (Kuhn et al. 2019) and that the inclusion of plant-based biogas digestate will lead to a substantial expansion of the required disposal area for organic fertilizer (Auburger et al. 2015). However, there are no studies available, yet, which assess the impacts of the revised FO 2017 on organic fertilizer transports comprehensively while considering the influence of heterogenous farming structures.

Another compliance strategy for biogas plants to meet the requirements of the FO is to reduce the inputs and thus reduce the amount of biogas digestate. However, since farms receive a guaranteed premium for the electricity they generate, a voluntary reduction of inputs is unlikely without a monetary incentive. One possibility is the provision of flexible electricity production which results in an input reduction, which is possible by a technical modification of the biogas plant. In the context of the energy transition, demand-driven electricity production from biogas offers an opportunity to compensate for fluctuating renewable energy types such as wind and solar power, which might justify an increased feed-in-tariff for biogas plants. In literature, multiple technical modifications of existing biogas plants have been investigated to determine the best solution for a demand-driven mode of operation (Lauer et al. 2017). Yet, none of the proposed solutions considered the possibility to reduce input levels in the generation of demand-driven electricity despite its potential to alleviate the environmental and economic burden of the expansion of the biogas sector.

The work presented in this thesis is primarily based on the results of the interdisciplinary research project “Modeling structural change and agricultural nutrient flows across scales in regions of North Rhine-Westphalia” funded by the Ministry of Environment, Agriculture, Conservation and Consumer Protection of the German state of NRW. The aim of the research project was to assess the impact of the revised FO 2017 by coupling the crop modeling framework SIMPLACE to the single farm level model FarmDyn and through a meta-model approach to the agent-based model ABMSim. The empirical case study region of the project and thus also from this thesis is NRW. NRW is characterized by a heterogenous land use structure with dense urban areas, livestock intensive regions, counties dominated by arable farming, and extensive farming areas. NRW has a high number of livestock farms with roughly 24.500 farms out of approximately 33.500 farms producing some kind of animal product in 2016 (IT NRW 2018). These livestock farms often coincide with one of the 620 biogas plants in NRW, which makes NRW number three in the ranking of number of biogas plants in Germany (LWK NRW 2017). Furthermore, NRW borders the Netherlands, a country which struggles to meet the targets of the ND, and thus exports large amounts of organic fertilizer into NRW, resulting in almost 8% of the total N from agricultural sources stemming from imports (LWK NRW 2018). The combination of livestock intensive farms and a high number of biogas plants which are predominantly regionally clustered as well as large quantities of organic fertilizer imports from bordering countries necessitates to address the impacts in NRW caused by the revised FO 2017 and 2020 on regional level as well as potential modifications in the subsidy scheme of the RES on farm level.

1.3 Structure of thesis and research objectives

The overall research objective of this thesis is to assess the policies which aim to alleviate the environmental impacts of the increased biogas production at farm and regional level. Derived from the problem statement, this thesis focusses on both the input and output side of the biogas fermentation process considering two strategies of farmers to comply with the measures of the FO. It addresses the reduction of inputs in the biogas production process at farm-level in Chapter 2. In Chapter 3 and Chapter 4, this thesis sets biogas digestate in the context of the organic fertilizer market and thereby allows to assess its role together with other organic fertilizer in the revised FO 2017 and FO 2020. To account for different spatial scales and policy detail each of the chapters uses a distinct methodological approach. This includes mathematical programming with the bio-economic single farm model FarmDyn (Chapter 2), calibration and application of a spatial price equilibrium model depicting the organic fertilizer market (Chapter 3), and the application of the agent-based model ABMSim simulating the organic fertilizer market through interaction of farmers in an auction setting (Chapter 4). An overview of the model types, their spatial scope, the assessed policy, and the level of analysis for each chapter is given in Figure 1.1.

	Chapter 2	Chapter 3	Chapter 4
Model type	Highly detailed bio-economic farm model - **FarmDyn**	**Spatial price equilibrium** model calibrated by a **bi-level estimation**	Agent-based model **ABMSIM** & **Meta-Model** based on FarmDyn
Spatial scope	Local	Regional (NRW)	Regional (NRW)
Assessed policy	RES - new subsidy scheme	Selected FO 2017 and 2020 measures	All FO 2017 measures
Level of analysis	Case study farms	County	County & farm type

Figure 1.1: Structure of the thesis with regard to model type, spatial scope, assessed policy and level of analysis

Remark: NRW – North Rhine Westphalia, FO – Fertilization Ordinance, RES – Renewable Energy Sources Act; *Source: Own depiction*

With a group of such diverse model types, the remainder of this section is not only dedicated to the individual research objective addressing the empirical application in the domain of biogas production but also motivates each methodological approach presented in the Chapter 2, Chapter 3, and Chapter 4.

The first part of the thesis explores the potential shift in the subsidy scheme of the RES to incentivize an input reduction in the biogas production and provide electricity flexibly. The rationale behind this proposed mode of operation in the biogas production aims at alleviating the burden of potential NO_3^- leaching from excess biogas digestate on water bodies while providing balancing energy. In order to estimate the required remuneration and assess which farm activities are affected the most by the input reduction, the bio-economic farm level model (BEFM) FarmDyn is extended and applied (Britz et al. 2019). The application of BEFM models such as FarmDyn in the evaluation of policies and adaption of new technologies provide several advantages. First, the detailed representation of technology allows FarmDyn to model different modes of operation in the biogas production and allows for a link between farm activities which include the connection of farm branches such as dairy and pig fattening farms with the biogas production process. Second, BEFMs are able to simulate farming activities and corresponding nutrient flows (Janssen und van Ittersum 2007), which enable the assessment of policies targeting management decision such as fertilizer use and investment in gas-storage systems. Third, BEFMs can be used ex-ante to assess potential policy measures (Blanco 2016) like the proposed new remuneration scheme for input reduced biogas production in the context of the RES. Two dairy farms with the two most prevalent biogas size classes in Germany serve as cases to examine the impact of the aforementioned subsidy scheme modification. The objective of the publication presented in Chapter 2 can thus be stated as:

(1) Estimating the required remuneration for different input reduction levels in demand-driven electricity production in biogas plants using the single-farm level model FarmDyn

Chapter 3 addresses the issue that on-farm nutrient concentrations stemming from biogas plants and livestock often exceed the allowed nutrient application which leads to exports of biogas digestate and other organic fertilizers. The distance and quantity of these exports can be amplified by tighter policy measures such as the assessed inclusion of plant-based biogas digestate in the revised FO 2017 and the reduced application limit of N in pollution hotspots in the revised FO 2020. Insights into emerging transport patterns are hence of importance to identify hazardous nutrient movements into pollution hotspots or other environmentally sensitive areas such as natural habitats. The prevailing modeling approach in the regional assessment of fertilizer policies is the application of a spatial price equilibrium (SPE) model which simulates the organic fertilizer market (van der Straeten et al. 2011; Willeghems et al. 2016). Traditionally, SPE models are used in the domain of single- or multi commodity trade analysis on country level to assess complex policy instruments (Paris et al. 2011). Crucial in the context of these SPEs and the assessment of the policy instrument at hand, is a calibration of the model. This step ensures that produced optimal (equilibrium) quantities do not diverge too much from observed ones, which occurs as unobserved transaction costs are not accounted for in the model. In the domain of organic fertilizer there are no studies available which apply any kind of calibration approach despite the fact that transports of organic fertilizer are subject to a multitude of transaction costs. These transaction costs include among others the search for potential trading partners, controlling for variation in nutrient quality, and establishing an understanding of peers in the community for potential odour hazards (Asai et al. 2014; Case et al. 2017; Tur-Cardonna et al. 2018). Chapter 3 addresses this issue of unobserved transaction costs by introducing a bi-level calibration approach to reproduce observed transports in NRW and thus implicitly capture these transaction costs. Consequently, the aim of Chapter 3 encompasses both an empirical part and a methodological part. In the empirical part, the revised FO 2017 with a focus on biogas digestate and the revised FO 2020 with a focus on N application limits in pollution hotspots is assessed. In the methodological part the bi-level application approach is introduced and discussed. The derived research objective can thus be stated as:

(2) Improved impact assessment of FO induced organic fertilizer transports using a bi-level programming calibration approach

Chapter 4 of this thesis expands the impact assessment on the organic fertilizer market by increasing the policy detail of the FO and zooming in on the transports between single farms in NRW. In addition to accounting for N from plant-based biogas digestate it considers simultaneously all other FO measures farmers have to comply with. To achieve such a detailed policy representation on a large scale such as NRW, the agent-based model ABMSim is extended and applied (Britz 2013). Agent-based models (ABM) provide the opportunity to combine the strength of farm level models, where single farms are depicted as agents, with the analysis of emerging phenomena at landscape scale which result from interactions among them (Happe et al. 2011; Huber et al. 2018). A crucial advantage of ABMs is the explicit decision behaviour depiction of agents in the interaction (Berger und Troost 2014; Schlüter et al. 2017; Huber et al. 2018), which allows to account for different types of actors in the organic fertilizer market in this thesis. In the application in ABMSim, it enables the integration of a FarmDyn meta-model to define the behaviour of livestock farmers. Such a model of a model makes it possible to utilize the high policy and technology detail as well as the assumed rational profit maximizing behaviour of FarmDyn for each livestock agent in the simulation of the organic fertilizer market. The meta-modeling approach using the single farm level model FarmDyn is based on previous research by Lengers et al. (2014) and was further developed by Seidel und Britz (2019) and Kuhn et al. (2019). This approach, which also draws from developments in FarmDyn presented in Chapter 2, reduces computational load, and thus facilitates the simulation of a farmer population size of approximately 33500 farms with heterogenous farm types acting in the organic fertilizer market such as dairy, pig and arable farms. The research aim of this part of the thesis can be summarized as:

(3) Investigating the impact on organic fertilizer transports induced by a complete accounting of FO measures with a heterogenous farm type population at the state level of NRW using the agent-based model ABMSim

In the following sections the contributions to literature and methodological discussions are presented. Each section is structured along the spatial focus of the developed and extended models from the on-farm model to the regional models. Finally, this chapter presents the policy implications derived from the modeling results.

1.4 Contribution and conclusion

1.4.1 Study outlines and major contributions

All subsequent chapters of this thesis address one of the defined research objectives above. In Chapter 2, this thesis explores a biogas plant operation mode which uses the reduction of inputs to dampen the demand of substrate and thus alleviate the pressure from biogas digestate on the environment. The reduced input levels allow for a demand-driven electricity production to harness high prices at the energy spot market; however, it also requires a modification in the RES scheme to compensate farmers for the reduced production of energy. This thesis finds that for all biogas plant sizes and RESs assessed in this thesis, the required remuneration is considerably high with 2.5 to 4 Euro cents per kilowatt-hour for input reduction levels over 35%. In general, required compensations are higher with installed biogas plants under the RES 2009 than the RES 2012 due to higher remuneration levels. Because of the cost efficiency objective of the RES and the fact that electricity from biogas is already the costliest renewable energy per kilowatt hour (Kost et al. 2018), the results of Chapter 2 highlights that it is difficult to justify the offer of such a RES scheme to biogas producing farmers.

Chapter 3 contributes to both the methodological advancement in the calibration of SPEs depicting the organic fertilizer market and the assessment of individual measures in the FO. In Chapter 3, the bi-level calibration approach is developed and applied in combination with the spatial price equilibrium model which depicts the organic fertilizer market including biogas digestate in NRW. The bi-level program is dissected into two tiers, where the upper problem tier minimizes the squared normalized difference between observed and estimated transports and the lower tier represents the SPE model which minimizes transaction costs of these transports. This thesis finds that the bi-level model setup improves the reproduction of observed transports in relation to the non-calibrated model with a mean absolute percentage error[1] (MAPE) of 9% in the calibrated model and 50% in the non-calibrated model for organic fertilizer transport flows between counties in NRW in the baseline. The MAPE reflects 47% of observed transport quantities compared to only 18% in a non-calibrated version of the model. It shows that the proposed calibration approach implicitly expands the drivers of transports from solely nutrient application limits set by the FO in the non-calibrated model to unobserved transaction costs in the calibrated model.

Furthermore, the analysis of the calibrated and non-calibrated model in the study presented in chapter 3 reveals that the unobserved transaction costs do not only impact the absolute increase in organic fertilizer in NRW in the aforementioned policy scenarios, but also that regional transport patterns diverge from each other. Contrasting the calibrated and non-calibrated model, our results indicate that organic fertilizer from regions high in N accumulation from agricultural sources are distributed both over short- and long-distances in the former model, whereas the latter model concentrate transports only in the direct vicinity of said regions in NRW.

In the empirical part of Chapter 3, this thesis contributes to the assessment of the revised FO 2017 and FO 2020 by investigating two individual measures. Specifically, it assesses the accounting of N from plant-based biogas digestate in the N application limit and a reduction of the total N application limit in pollution hotspots. This thesis finds that the highest inter-county transports are to be expected in the northwest of NRW where livestock intensive and biogas plant rich counties are bordering those with nutrient absorption capacities, however, longer-transport distances are also observed. Increases in net-exports on county level in these regions

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[1] The mean percentage error (MAPE) is used as a measure to evaluate forecasting models (Myttenaere et al. 2016.

range from 5 up to 25 kg N ha^{-1} which partly leads to a doubling of transported organic fertilizer in those counties.

In Chapter 4, the agent-based model ABMSim is extended to depict the organic fertilizer market in a ‘bottom-up approach’ with individual farms. The organic fertilizer market is constructed such that livestock farmers and arable farmers are trading organic fertilizer including biogas digestate in an auction setting. The decision behaviour of livestock farmers is based on a meta-modeling approach in which simulation results of the highly detailed single-farm level model FarmDyn are used to estimate an organic fertilizer export function. In our application, we show that the use of such a meta-modeling approach allows to implicitly implement the entire FO including all relevant nutrient thresholds and at the same time account for biogas digestate in the export quantities. In addition, the application of the meta-model reduces the computational load in comparison to small mathematical programming models which are traditionally used in ABMs in the domain of agricultural economics. This thesis shows that combining both aforementioned advantages of the meta-model enables a comprehensive large-scale impact assessment with approximately 33.500 individual farms and more than 35.000 km^2.

A further contribution of the work presented in Chapter 4 is the generation of a synthetic farm population based on the Farm Structural Survey (FSS) under restricted data access (Statistische Ämter des Bundes und der Länder 2017), which resembles the true farm population of NRW closely. The synthetic farm population is developed by using publicly available data on county and communal level in a highest-posterior density (HPD) estimation approach. The estimation approach generates information about the number of certain farm types in their respective size classes on communal level. Combined with information from the farm typology developed by Kuhn und Schäfer (2018), it enables to account for regionally heterogenous farm structures and thus allows to assess the regional impact of relevant farm type specific nutrient application limits. More generally, the presented approach can be used to develop a synthetic farm population for other regions and thus serve in the policy assessment where regional heterogenous farm structures are of relevance.

Combining the insights of the results of Chapter 3 and Chapter 4, this thesis finds that two FO 2017 measures are contributing to the increase in export quantities and transport distance. First, as the inclusion of plant-based biogas digestate in the N application limit increases the total amount of N which has to be accounted, it leads to increased transport distances and quantity. This is due to both a reduction in the nutrient absorption capacities of accepting farms and the increased required export quantities by biogas plant operating farmers and other agricultural holdings. Second, the high share of P_2O_5 in pig manure leads to P_2O_5 saturated soils in regions characterized by intensive pig fattening farms. In interaction with the stricter P_2O_5 balance threshold in the revised FO 2017, large increases in export quantities and transport distances are triggered, however, solely affecting pig farms. This P_2O_5 balance threshold leads, in this context, to another counterintuitive emerging phenomena. As organic fertilizer contains both N and P_2O_5, the exported quantities induced by the P_2O_5 threshold lead not only to an export of P_2O_5 up to the allowed limit but also to simultaneous reduction of N on these farms. In Chapter 4, this thesis shows that through the regional cluster of livestock intensive farms including pig fattening farms in combination with the P_2O_5 balance threshold, a regional reduction of N quantities on communal level emerges. Due to the high concentrations of pig fattening farms in some communes in the northwest, this thesis shows that this revised FO 2017 measure can unintentionally lead to a decline of up to 65 kg N ha ^{1}; and thus, diminish the thread posed by NO_3^- leaching to ground- and surface water bodies in the exporting regions.

In both Chapter 3 and Chapter 4, this thesis finds that long-distance transports are increasingly prevalent in livestock intensive regions due to the revised FO. From an environmental perspective, these increased transport distances can lead to pollution swapping. Pollution swapping is defined as either a shift of pollution between environmental indicators, such as for example from NO_3^- leaching caused by N application to carbon dioxide emissions made by transports, or between regions where NO_3^- leaching in one region is replaced at the cost of NO_3^- leaching in another region (Oenema und Velthof 2007). In Chapter 3, the results highlight that the latter definition becomes primarily relevant in the results of the calibrated model version where the most stringent policy scenario from the revised FO 2020, in terms of reduced total N application limit, leads to considerable organic fertilizer transports of more than 50 kg N ha^{-1} into regions far off from livestock hotspots. In Chapter 4, the increased transports are triggered by taking the full set of measures of the revised FO 2017 into account, especially, the P_2O_5 balance threshold which forces pig fattening farms to increase transport distance in livestock intensive regions. The results indicate a relevant range of transported N in regions with accepting farmers and hence contribute to help by identifying potential regions prone to spatial pollution swapping.

1.4.2 Methodological discussion and research recommendations

In this thesis multiple model types spanning from local to regional level are developed or expanded to assess environmental and economic impacts of biogas production and its by-product biogas digestate in the context of the revised FO 2017 and FO 2020. The presented methodological discussion in the following section is structured along its spatial scale from local level in Chapter 2 and parts of Chapter 4, followed by issues discussed for the regional models in Chapter 3 and Chapter 4. Eventually, methodological implications, which arise through the choice of the model type in Chapter 3 and Chapter 4, are contrasted.

In Chapter 2 and Chapter 4, the highly detailed bio-economic single farm level model FarmDyn is applied. In Chapter 2, FarmDyn is used to assess a proposed shift in the RES subsidy scheme for biogas plants, whereas in Chapter 4, FarmDyn is used to generate simulation results for relevant variables in organic fertilizer export decisions for a large number of farms. The advantage of single farm level models is the highly detailed technology representation and the possibility to introduce complex policy measures (Janssen und van Ittersum 2007), which is used in both applications. In Chapter 2, it facilitates the connection of policy and technology where a limit on input use is exogenously introduced into the fermentation process which enables to assess the required increase in RES remuneration to compensate for profit losses. In Chapter 4, this thesis draws from previous modeling work (Kuhn et al. 2019; Kuhn et al. 2020), which introduced the FO and an improved fertilization activity into FarmDyn. The modeling work was conducted in the interdisciplinary research project mentioned in Chapter 4, which coupled a crop modeling framework (SIMPLACE) with the single farm level model FarmDyn and the agent-based model ABMSim. Both applications benefit from the advantages of single farm level models, however, they also have to consider price exogeneity as a major shortcoming both in the analysis in Chapter 2 and in the estimation of the meta-model and its implication in the ABM in Chapter 4. The lack of market feedback, in Chapter 2, neglects the impact of a reduced biogas substrate demand on its regional prices which are the major driver of biogas plant profitability. Further, the increase in required remuneration is highly dependent on the spread between the daily peak price and the lowest price for electricity on the spot market which are, inter alia, determined by the daily demand fluctuations, prices for gas, coal and oil, and electricity production of intermittent renewable energy sources (Paraschiv et al. 2014; Bublitz et al. 2017). One way to improve the assessment in future studies is to link the single farm level model to regional market models which include both agricultural markets and the energy market. An example for such a connection is provided by (Petig et al. 2019) where the supply prices for the single farm level model are given by the partial equilibrium model ESIM and the energy sector model TIMES-PanEU to assess different bioeconomy scenarios. In Chapter 4, FarmDyn is loosely linked to the agent-based model ABMSim, which would make further model connections relatively more challenging. However, the design of experiments for the estimation of the meta-model already integrates the variation of one of the most important exogenous prices in export decisions, namely transportation costs of organic fertilizer. Through the variation in the experiments, it allows to account for different prices in the organic fertilizer market in ABMSim, however, other relevant exogenous prices such for the primary outputs, namely pork and milk, are not considered to vary, even though their impact on the organic fertilizer export decision is highly relevant, and hence could be assessed in sensitivity analysis in future research.

In Chapter 3, a SPE model is developed in which a bi-level calibration approach is used to reproduce observed nutrient transports by adjusting transaction costs. Spatial price equilibrium models are advantageous to assess the impact of complex policy instruments on trade as they can reproduce observed transport flows between trading entities (Paris et al. 2011). In the domain of organic fertilizer markets, this model type enables to determine policy induced changes of regional nutrient distribution through organic fertilizer transports. A limitation in the construction of the organic fertilizer market in Chapter 3 is rooted in the sparse data on organic fertilizer transports. The data is only available as aggregate information on N and P_2O_5 supply by various agricultural sources, which includes plant-based biogas digestate, and the respective nutrient flows between counties. This limited data base prevents a distinction between different manure types in the SPE model and thus leads to the assumption of the homogenous product N in the model application which restricts the representation of the multi-nutrient targeted policy design of the revised FO. Specifically, this limited information inhibits a further disaggregation of organic fertilizer into its subtypes with their varying nutrient compositions. For example, pig manure contains relatively more P_2O_5 than N compared to cattle manure, whereas the nutrient content of biogas digestate depends on its input composition. Consequently, in a real world setting distinct nutrient application thresholds of the FO become relevant in the induction of organic fertilizer transports depending on manure type. An option to integrate measures for other nutrients such as a P_2O_5 balance threshold under given data restrictions is to introduce county specific manure compositions where the nutrient ratio $N:P_2O_5$ is based on the accumulation within one county given by the data for NRW. This implicitly depicts the animal and biogas plant structure of the county and thus would account for an approximation of manure type specific transports.

Furthermore, the generation of county specific manure compositions would allow to address another issue inherent in SPE models. Bi-lateral transports, i.e. counties importing organic fertilizer from another county while exporting to that county simultaneously, are often observed in NRW (LWK NRW 2018). This transport pattern occurs primarily when two communes in neighbouring counties are spatially closer to each other than communes within their respective county. However, SPEs neglect such bi-lateral transports as they contradict the assumption of cost minimizing behaviour in the model. To circumvent this downside, traditional models draw on the Armington assumption (Armington 1969), which states that homogenous products from two different trading partners are considered heterogenous based on their origin (Paris et al. 2011). Here, the county specific manure compositions would enable a heterogenous product transported and thus constitute a solution to the bi-lateral transport problem.

ABMs, as the third model type applied in Chapter 4, are suitable to assess the revised FO on regional level while accounting for farm heterogeneity and a high policy detail in the model. One of the primary advantages of ABMs is the flexible implementation of behavioural assumptions of single agents. The decision behaviour in the interaction between agents in the presented ABM is the applied meta-model which estimates organic fertilizer export quantities. The application of the meta-model reduces the computational load and therefore allows to address limitations in the regional and policy scope usually encountered in ABMs. Thereby, it facilitates an NRW wide assessment of the FO, which is relevant in view of the stricter measures and the resulting increase in transport quantity and distance. However, the applied organic fertilizer function as a meta-model has drawbacks as it cannot consider changes in the farm endowments as a feedback to outcomes on the organic fertilizer market. For example, instead of transporting over long distances, which occurs when no farmer who is willing to accept the organic fertilizer is found in the vicinity, farmers could reduce their livestock as it is economically more viable. Hence, this would rather target the reduction of the overall regional N burden than a shift of the high N levels into regions which have the possibility to absorb further quantities. In order to tackle this shortcoming, ABMSim could either implement small single farm level models or introduce other types of decision behaviour such as heuristics or other meta-models. Farm level models which are specifically designed to encompass only activities and nutrient flows relevant for the FO, however, are likely still to computationally challenging to solve considering the presented population and spatial scale. In the realm of meta-models, recent developments in machine learning have the potential to replace econometrically estimated meta-models. One such an example would be a neural-network which can be trained by both generated or observed data to depict the input-output relationships of a farm. Here, the generated data set, as presented in Chapter 4, could add input-output relationships tailored to the research question at hand. In the context of the organic fertilizer market, a marginal value on the right to emit a kg of N could be determined in FarmDyn and thus implemented in the training of the neural network. As a result, the neural network can be used to represent the farm in general, whereas the marginal value would be employed in the decision behaviour of farmers on the organic fertilizer market in the auction setting of ABMSim.

The farm population for NRW in ABMSim is based on the FSS. The FSS is an official statistic which covers key farm characteristics on nearly all farms in Germany. However, there are multiple limitations related to the assessment of the revised FO with respect to the organic fertilizer market in general and to biogas digestate specifically. First, the official statistic is accessible in all its details at designated workstations in federal statistical offices, however, only limited data processing and extraction is allowed due to data security issues. As a result, generating a detailed breakdown of farm types to develop a more heterogenous farm population is not possible, which prevents to take advantage of all available farm branches in FarmDyn. Consequently, the use of only dairy and pig fattening farms as proxy farms for a more diverse livestock farming population influence the results with respect to transport quantities and distances. Second, often larger farms with multiple farm branches are split up into legal units due to tax regulations, which are then represented as single farms in the FSS (Forstner und Zavyalova 2017). In the application in ABMSim this can lead to extremely high organic fertilizer export quantities for farms which only represent the legal unit of the livestock branch. Third, the FSS does not provide any information if farms own a biogas plant nor if a group of farms share a biogas plant. Thus, in the application in ABMSim we refrained from connecting biogas plants and farms. However, data from the nutrient report on biogas digestate quantities is available at county level, which we used to distribute the N from the digestate equally over all farms. The distribution of biogas digestate in that way assured that the regionally occurring biogas digestate is accounted for and its impact in the context of the revised FO can be assessed.

The models presented in Chapter 3 and Chapter 4 have inherently different approaches to develop a baseline for the FO assessment and thus deviate in their ability to capture observed transports. The model structure of the SPE model allows to use the bi-level calibration process to reproduce parts of the observed transports by adjusting transaction cost parameters. ABMs do not enable such calibration methods but have to rely on a validation procedure. Due to the flexible setup of ABMs, assumptions with respect to decision behaviour and interactions between farmers can be adjusted and their impact on the outcome can be validated by comparing said outcome to observed values. These assumptions can be linked, for example, to the willingness to accept organic fertilizer on farm, which are captured implicitly in the SPE model. In literature, however, the use of imported organic fertilizer is determined by a wide range of potential reasons which include uncertainty about nutrient contents, odour pollution, buying and application costs, timely delivery, and experience in the handling and use of organic fertilizer (Asai et al. 2014; Case et al. 2017; Tur-Cardonna et al. 2018). Such a variety of reasons makes it difficult to identify the most relevant factors for the validation procedure in the ABM as they might even differ regionally, for example, when odour hazards become a higher hurdle to import organic fertilizer in urban areas than in areas accustomed to the application. In future research projects, the information generated on implicit transaction costs in the SPE model can be used in the validation process of the ABM by introducing more stringent assumptions for accepting organic fertilizer in regions with high transaction costs and relaxing the assumptions in those regions with low transaction costs.

In the model applications in Chapter 3 and Chapter 4, the assumptions made on the organizational structure of the organic fertilizer market in NRW differ strongly between both models and also deviate from the real-world organic fertilizer market. The SPE model in chapter 3 assumes that the organic fertilizer market is organized under perfect competitive market conditions with a transaction cost minimizing arbitrageur. In contrast, the organic fertilizer market in ABMSim handles the interactions between livestock farmers and arable farms in an auction setting which mimics a next-neighbour approach based on the assumption that distance is the only relevant transport cost determinant. Both assumptions capture elements of the real-world settings, however, neglect other relevant parts. Similar to the spatial arbitrage assumption in the SPE model, a nutrient exchange in NRW (Nährstoffbörse NRW n.d.) organizes a share of the organic fertilizer transports through a cooperation between agricultural contractors which try to reduce the costs stemming from the distribution of organic fertilizer. However, in the real-world many of the organic fertilizer transports are bilaterally arranged between farmers often within the direct vicinity, which resembles the next-neighbour approach in the auction mechanism in ABMSim. In order to improve the representation of the organic fertilizer market and thus to allow a more refined assessment of the FOs in future research, the flexible agent and decision behaviour structure of ABMSim can be extended. New agents could be introduced such as contractors which mimic the behaviour of nutrient exchanges by collecting a certain share of organic fertilizer within their vicinity and organizing as well as performing the transports and application. Further, new rules for farmers could be implemented which tackle the aforementioned transaction cost related factors. Such factors could address the accepting decision such as odour hazards in urbanized regions, level of experience in the application of organic fertilizer in their peer group, availability of application techniques by local contractors, or uncertainty in the nutrient content of organic fertilizer. Nevertheless, when extending ABMSim with new behavioural assumptions or agents, they would necessitate a sound empirical foundation and validation.

Both regional models presented in Chapter 3 and Chapter 4 assume that biogas digestate and organic fertilizer in general is transported untreated, which means that the liquid and solid fractions are not separated through mechanical, chemical, or thermal processes. There are many studies in literature investigating the benefits on economic and environmental level of such separation processes as they enable to apply the liquid part, which has high transport costs per km due to the high water content, close to the processing facility and transport the solid part over long distances as the nutrient density in this fraction is higher (Hjorth et al. 2010; Aguirre-Villegas et al. 2019). The separation process would also lead to a change in nutrient composition in the partitioned fraction with a higher P_2O_5 share in the solid fraction and a higher share of N in the liquid fraction compared to the initial organic fertilizer. In future application, both aspects, the differentiation of a solid and liquid fraction and their different nutrient composition, can be introduced as a technology option in FarmDyn and thus through a meta-model implemented in ABMSim to investigate the facilitation of longer transports through reduced transport costs. In contrast, as no explicit technology can be introduced in the SPE model, an analysis would be limited to the reduced transports costs based on the cost reduction.

1.5 Policy implications

Since the RES 2014 the support for the biogas sector focused on two biogas plant types. First, small biogas plants with manure as their primary input were promoted to generate electricity with methane contained in the animal excrements. Second, instead of continuing to support the expansion of biogas plant numbers, the RES 2014 and 2017 promoted the demand-driven electricity production from existing biogas plants. In Chapter 2, this thesis assessed a potential remuneration scheme which aimed to incentivise a demand-driven electricity production of existing biogas plants; however, results showed an unlikely adoption of this payment scheme by policymakers due to the high additional costs. Instead, the government introduced a tender procedure to promote flexible electricity production by assigning energy production capacities to farmers who are able to generate electricity the cheapest. This procedure was developed for new and existing biogas plant which enabled bidders to secure a remuneration level for the electricity produced after the construction of a new plant or an extension of an existing one (BMWI 2014). It was primarily used by existing biogas plants which aimed at securing further payments after their remuneration scheme of 20 years runs out. This led to a development in the biogas sector of increased installed electric capacity to generate more electricity when needed, while the actual substrate input in the fermentation process remained almost constant (Daniel-Gromke et al. 2019). Eventually, new investments in the biogas sector both in small manure run biogas plants and modified existing biogas plants did prevent a further environmental burden created by nutrients from plant-based biogas digestate.

This thesis shows in Chapter 3 and Chapter 4, short- and long-distance transports and transport quantities of biogas digestate and organic fertilizer in general increased due to stricter measures of the FO. Based on the current state-wide support framework to facilitate organic fertilizer transports in NRW, it can be assumed that such a development is politically intended to prevent large disruptions of the farming structure. This thesis gives insights in the spatial distribution of N caused by the organic fertilizer transports in NRW and thereby helps to identify regional clusters and farm types most affected by the emerging transport patterns. Based on the findings, new support measures and enforcement strategies can be developed, which are discussed next to the existing support framework in the following.

A corner stone in the supporting measures for organic fertilizer transports is the financial assistance of the nutrient exchange by the state of NRW. The nutrient exchange is a group of certified arbiters comprising independent contractors and laboratories, as well as consultants of the chamber of agriculture. The nutrient exchange provides a range of services with the aim to reduce transaction costs for farmers by assisting in finding trading partners, organizing logistics and application of the organic fertilizer, and determining nutrient contents in organic fertilizer in their laboratories. The majority of the contractors and laboratories in the nutrient exchange coincide spatially with the livestock intensive regions in NRW. This leads to a void of supporting companies and infrastructure to handle large quantities of organic fertilizer in arable farm dominated regions further away. Given the fact that transports into those regions is likely to increase, investment support for storage facilities and organic fertilizer application machinery can facilitate uptake of organic fertilizer by both farms and contractors.

Distance related transport costs remain one of the primary obstacles to prevent transports in regions with nutrient absorption capacities. There are several publicly funded research projects and seminars targeting reduced transport costs of biogas digestate and organic fertilizer in general (Cielejewski 2013; LWK NRW 2011; 3N Kompetenzzentrum n.d.). These include the application of separation technologies to divide the solid from the liquid fraction of organic fertilizer and the use of specialized lorries which can transport organic fertilizer on the outward and agricultural products such as cereals on the return journey. Against the background that regional clusters of pig farms in NRW are the major determinant for long-distance transports, separation technologies which concentrate P_2O_5 in the solid fraction can play a critical role in mitigating the economic pressure on these farms and contribute to a more sustainable P_2O_5 use in the agricultural sector. Here, the supporting framework for exporting farms could be expanded by either providing financial incentives for farms to install separation machines or for contractors to procure mobile separation machines in livestock intensive regions. However, before the implementation of supporting measures for processing techniques, a meticulous assessment of their potential environmental impact and resulting pollution swapping is advisable (Vries et al. 2012; Hoeve et al. 2016).

The emerging transport patterns and the resulting shift in N distribution in the simulations in chapter 3 and 4 indicate that the threat to groundwater bodies imposed by regional pollution swapping has to be considered when designing the support system for organic fertilizer transports. This becomes especially relevant when county wide kg N ha^{-1} levels strongly deviate from expected NO_3^- levels in their respective groundwater bodies. For example, counties in the southwest of NRW which experience high organic fertilizer imports in the simulation results due to high nutrient absorption capacities are partly marked as pollution hotspots according to the FO 2020 as their respective groundwater bodies almost or already exceed the NO_3^- limit of 50 mg l^{-1} (LANUV 2020). A first step to prevent such detrimental transports are introduced by the FO 2020 which provides stricter measures for pollution hotspots (BMEL 2020). However, to identify the causes of the aforementioned deviations and to ensure that the imposed measures are sufficient in attaining the targets, monitoring and research efforts have to be made. Eventually, resulting insights can be used to determine interactions with the potential support system.

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Chapter 2

Flexible load of existing biogas plants: a viable option to reduce environmental externalities and to provide demand-driven electricity?[2]

Abstract

The expansion of fluctuating renewable energies such as wind and solar increases the need for electricity produced on demand to stabilize the grid. Electricity from existing biogas plants in Germany allows flexible energy output and is increasingly marketed on demand requiring technical modifications such as increased gas storage and engine capacity. In this study we investigate an alternative approach in which a reduced fermenter load provides additional gas storage and engine capacity with no additional investment. This reduces input use and digestate production, thereby decreasing environmental externalities in regions with high biogas and animal densities. We quantify the required increase in subsidies for two dairy farms in Germany to switch from guaranteed subsidies for continuous electricity production to different levels of flexible load. The farms are assumed to have invested in a biogas plant under the Renewable Energy Sources Act (RES) of 2009 and 2012. We simulate the reduced biomass demand and its implications on farm management with a focus on fermenter input composition. Thereto, we develop a bio-economic model of a biogas plant and integrate it in the dynamic single-farm model FarmDyn. We find that provision of electricity on demand reduces especially the demand for maize silage, a feedstock with high negative environmental externalities. Even a moderate input reduction of 30% requires a subsidy increase of 1.8 to 3.2 cents/kWh contingent on the initial RES. We conclude that despite the approach being able to provide electricity on demand and to reduce negative environmental impacts, a widespread application seems unrealistic due to high additional subsidies.

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Keywords: Biogas; Policy; Flexible electricity production; Biogas plant feedstock; Environmental impacts

2.1 Introduction

As a continuation of efforts towards a low carbon economy in the European Union, the European Council agreed upon the "2030 framework for climate and energy policies (European Commission 2014). It sets targets for reducing greenhouse gas (GHG) emissions by 40% and increasing the share of renewable energies and energy efficiency by 27% by 2030, respectively. Germany fosters the expansion of renewable energies since 2000, especially in the electricity sector, by the so-called Renewable Energy Sources Act. It aims to mitigate GHG emissions and further negative external effects attributed to the use of non-renewables while at the same time protecting the environment (BMELV 2007; BMWI 2011). The RES promotes both intermittent and continuously producing renewable energies through fixed feed-in tariffs (FITs), guaranteed over two decades, and market premiums for participants in a direct marketing scheme. These subsidies rendered investments in renewable energies profitable while largely reducing market risks, resulting in a share of 25.8% of renewable energies on the gross electricity consumption in 2014 (BMWI 2015).

While the biggest share is derived from wind energy, bioenergy contributed about 6.9% to the gross electricity production in 2014. Bio-energy use promoted by the RES focuses on electricity – the bio-fuel sector is not part of the act – which comes primarily from decentralized biogas plants. Whereas in 2004 biogas plants produced less than 500 MW electricity, the amount increased sevenfold to over 3900 MW per year in 2014 (Fachverband Biogas e.V. 2015). This increase was triggered by the first RES amendment in 2004 which promoted the use of energy crops by changes in the FITs for biogas production; this subsidization continued until the RES 2012. However, that massive expansion of biogas production was only feasible with a substantial increase in biomass use of energy crops: in 2014, 7% of the agriculturally used area in Germany was devoted to feedstock production for biogas, of which 63% was energy maize (DeStatis 2014).

2.1.1 Environmental and economic implications of extended biomass demand

It is increasingly acknowledged that the high demand for energy maize contradicts the environmental protection objective of the RES. Loss of biodiversity, increased soil erosion and ploughing up of permanent grassland are attributed to expanded energy maize cultivation which is often cropped as a monoculture (EEA 2007;

Osterburg und Röder 2013). Integrating biogas production in existing farming systems under the subsidies of the RES, at least until 2012, drove up the overall biomass demand, as the low energy concentration of substrates such as animal excrements or plant based by-products does not suffice for a production of relevant amounts of bioenergy and renders the process quite expensive. Even with considerably increased shares of crops such as maize, which produce more biomass per hectare relative to other crops, the additional biomass demand of a biogas plant requires additional imports of either compound feed or fodder into the farm, the latter either used for animals or biogas production (Britz und Delzeit 2013).

The RES rendered investments into biogas plants especially lucrative for farms (or group of farms) with high animal densities. That was due to high FITs for the use of moderate mass shares of manure in the RES 2009 – which contributed little to overall energy output due to their low energy concentration - and favorable accounting rules for nutrients from biogas plants in environmental law. Consequently, after investing into biogas plants, farms typically disposed higher organic nutrient loads on their own or neighboring plots. Already often high nutrient surpluses were driven further up and enforced threats to ground and surface water (Heidecke et al. 2012; Guenther-Lübbers et al. 2014).

Besides environmental issues, the additional biomass demand for biogas production impacts land lease and fodder prices, potentially crowding-out other types of agricultural production and their respective value chains (Rauh 2010; Emman et al. 2012; Emman et al. 2014). The German government reacted to these negative effects in a RES amendment in 2012 by decreasing incentives for the use of energy maize. As electricity production from biogas, compared to other renewable energies, is rather expensive, the subsequent RES amendment in 2014 lowered the FITs for newly erected biogas plants to a level where new investment into biogas plants and thus a further expansion of the sector seems unlikely (Scheftelowitz et al. 2014). In addition, this latest amendment prescribes a maximal expansion of installed electric capacity of 100 MW from biogas per year (BMWI 2014). However, the reader should keep in mind that all existing plants benefit from the FITs guaranteed in the legislation when they were built if the operator did not opt to switch to a newer legislation. Due to sunk costs and guaranteed output prices, these existing plants will operate typically from the year of installation onwards for the full period of guaranteed FITs, i.e. for 20 years. With the sharp increase in new constructions especially in the years 2004 to 2010, the consequences attributed to the biogas sector will hence be felt until 2030.

2.1.2 The role of flexible electricity production of biogas in the energy transition

The German government fosters the replacement of nuclear and fossil fuels with renewable energies within the electricity sector in the so-called energy transition (Strunz 2014). Consequently, reducing the costs of electricity produced from renewables by limiting further increases in the expensive biogas sector in favor of cheaper renewables such as wind and solar, corresponds to the renewable expansion goals of the energy transition. However, most alternatives to biogas, such as wind and solar, lead to volatile electricity output and thus require balancing energy sources, as technologies to store electric energy at industry scale have not yet reached market maturity. Here, despite higher costs, electricity from biogas production could play a role as biogas could be stored and electricity produced on demand at times when output from other renewable sources is low (Auburger und Bahrs 2013). Accordingly, the recent amendments of the RES in 2012 and 2014 introduced incentives for flexible electricity production from biogas to promote market integration and demand-driven electricity production. As a further expansion of the biogas sector at the low FITs for new investments is unlikely, this flexibilization approach mainly targets the current biogas inventory. Based on a survey, Scheftelowitz et al. (2014) estimated that 8% of the existing plants already produce electricity flexibly based on direct marketing.

The most commonly used biogas plant setup for flexible electricity production is based on continuous biogas output, buffered by extra gas storage and engine capacity (Hahn et al. 2014). In case of higher demand, power engine output is increased by adding biogas from storage to the continuous output from the fermenter. Accordingly, a larger combined heat and power engine capacity relative to the size of the biogas fermenter plus storage capacity is necessary. That storage capacity and the potential of the engine to convert biogas beyond the continuous output from the fermenter define jointly the maximum flexible load and drive-up investment costs. Several studies investigated the economic viability of this biogas set-up and found that flexibly produced electricity could be provided without additional subsidies (Hochloff und Braun 2014; Barchmann und Lauer 2014). While these studies focus only on the economic viability of flexible electricity production, to the knowledge of the authors no study exists, which examines a biogas plant setup taking the aforementioned environmental and agricultural sector concerns into consideration.

2.1.3 Investigating the influence of reduced biomass demand

Based on this background, we aim to fill the gap in literature by taking agricultural economic and environmental impacts of existing biogas plants into account and propose a biogas setup for flexible electricity production with reduced biomass input. In contrast to the aforementioned studies, the larger combined heat and power engine capacity relative to the size of biogas plant is not achieved by increasing power engine and gas storage but by reducing the continuous biogas production through decreased biomass input. This study has thus two main objectives: first, to investigate the economic viability of such a biogas setup by quantifying the required increase of subsidies for different levels of desired flexibility. Second, to examine related changes in farm management, in particular biomass demand differentiated between source and crop. In order to achieve the objectives, we develop an economic supply-side biogas model based on fully dynamic mixed integer linear programming (MILP) approach which simulates simultaneously the economic and technical aspects of a biogas plant. As most biogas plants in Germany are linked to an existing farm, the biogas model is integrated as a module into the existing bio-economic FarmDyn model (Britz et al. 2019).

The remainder of the paper is structured as follows. Section 2.2 presents the modeling framework for the biogas plant. Further, it introduces the economic and technical aspects of the biogas model as well as the data basis. In addition, the farms and amendments which will be investigated are presented. Section 2.3 examines the results and discusses their implication with respect to potential environmental and economic benefits as well as discussing the role of biogas in the electricity sector. Finally, Section 2.4 summarizes and concludes the findings of this study.

2.2 Methodology

2.2.1 Modeling framework

The biogas plant is integrated in the highly detailed bio-economic single farm-level model FarmDyn[3] realized with the General Algebraic Modelling Systems (GAMS) language. FarmDyn is an economic supply-side model building on fully dynamic MILP. The linear programming approach facilitates the depiction of technological and economic activities as linear combinations (Berge et al. 2000). These activities are defined by input-output coefficients (Hazel und Norton 1986) to return e.g. the

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[3] For further information on FarmDyn please consult the technical documentation BRITZ et al., 2016.

generation of electricity or the production of substrates for the biogas plant. The high detail of FarmDyn is advantageous as the additional incentives necessary for flexible electricity output are contingent on technological aspects such as the input mix used in the fermenter while reduced biogas demand impacts farm management.

Extending linear programming with a mixed integer approach serves two purposes. On the one hand, the MILP approach depicts correctly non-divisibility of investment decisions (Ciaian et al. 2013) such as reinvestments of existing biogas plant parts which differ in physical lifetime. In our setup, also part of off farm work is captured by integer variables. Furthermore, it allows for strategic decision options (Janssen und van Ittersum 2007), as for example in our application a switch between different amendments of the RES. In addition, the fully dynamic approach simultaneously depicts the full planning horizon (Gallerani et al. 2013), allowing a detailed assessment of future returns to alternative investment decisions. As discussed in the result section, this encompasses re-investments in dairy stables and equipment.

We assume a rational and fully informed decision maker maximizing the net present value (NPV) over a predefined planning horizon; in our application covering the two decades for which FITs are guaranteed. Even though several authors propose a risk-averse decision maker (Pannell et al. 2000; Janssen und van Ittersum 2007) maximizing over multiple objectives (Berge et al. 2000) in a farm-household context, risk neutrality is chosen in here for several reasons. It renders result analysis straightforward as the derived increases in subsidies relate to costs only and do not comprise risk premiums. The latter would reflect our assumptions on risk behavior for the hypothetical case study farms, with little empirical content. And finally, the combination of a fully dynamic optimization and the MILP approach within FarmDyn render the model already quite large and limit further extensions due to computational restrictions.[4]

The optimization problem is constrained by possible production patterns, willingness of the family to work on farm, liquidity constraints as well as policy and environmental restrictions.

The biogas module is integrated as a farm branch module which is consistently interlinked with mass flows and the economic optimization section of FarmDyn. It covers the cash flows, accommodations of loans, variable - and investment costs, distribution of work and the calculation of the net present value of cash balance. In

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[4] A stochastic programming extension based on stochastic trees for FarmDyn where all variables are stage contingent has been recently developed, but the complexity of the model severely restricts the size of the decision tree. Applications are still experimental and deemed not appropriate for the current study.

addition, the required biomass for the biogas production process can be either delivered from own production depicted by the manure and cropping modules or can be purchased.

The biogas module covers the technological and economic aspects of a biogas plant including the RES amendment specific restrictions and payment structures. In addition, the investment part of the biogas module covers the necessary reinvestments to keep the existing plant operational. These three essential aspects - investments, biogas and electricity production and related revenues and costs - are discussed in the following.

Investment part

The maximal number of biogas plants per farm is set to one in the model. Besides the initial investment, continued use of a biogas plant requires reinvestments in intensively used machinery parts shown in equation (1). The model differentiates machinery parts by investment horizon, i.e., the combined heat and power engine has to be replaced every 7 years whereas the existing mixer in the fermenter as well as the mixer in the storage for digestates has to be replaced every 10 years. Constructions such as the fermenter or the substrate storage have to be replaced every 20 years. The corresponding costs for different biogas plant sizes, investment horizons and credit rates are shown in Appendix 2.1. The overall investment costs for a biogas plant in each year are calculated in (2) and are integrated in the overall yearly investment costs of the farm in FarmDyn.

$$I_{ih,b} \leq \lambda_{ih,b} + B_{ih,b} \tag{1}$$

$$\Gamma_b = \sum_{ih} B_{ih,b} * \pi_{ih} \tag{2}$$

where $I_{ih,b}$ is the biogas parts inventory for each biogas plant part *ih* and biogas plant size *b*, $\lambda_{ih,b}$ is the biogas inventory prior to the simulation, $B_{ih,b}$ is the bought inventory during simulation, Γ_b are the biogas plant parts investment cost and π_{ih} is the price of each biogas plant part.

Technological part

The biogas and electricity production process for each month is described as a Leontief production function constrained by technological and biological process restrictions shown in equation (3) to (8). Electricity output depends on input quantities, the methane content of inputs, energy content of methane and the electric conversion efficiency of the engine (3). The production process of heat differs from the electricity production process only in the conversion efficiency and is not shown here in addition. The electricity production is constrained by the maximal capacity of the engine in kW to convert electricity (4).

$$Y_b = \sum_i (X_i * \varepsilon_i) * \omega * \eta_b \tag{3}$$

$$Y_b \leq I_b * \alpha_b \tag{4}$$

where Y_b is the electricity output for each biogas plant size b, X_i is the biomass input for each input i, ε_i is the methane content per ton fresh matter, ω is the energy content in kWh per m^3 methane, η_b is the conversion efficiency for electricity for each biogas plant size and α_b is the maximum capacity of the combined heat and power engine.

Equations (5) and (6) describe the technological constraint that the input amount cannot exceed the net-volume of the fermenter[5]. Further, equation (6) includes a parameter to restrict the fermenter load to a certain maximum level. This parameter ϕ is used to quantify the FIT levels for different input amounts. In addition, the production process in the module is constrained by restrictions prescribed by legislation to receive additionally bonus payments or payments at all. The model includes the bonus payments for manure use in the RES 2009, where 30% of the input volume has to be manure sourced to receive the bonus. Further, it accounts for the fact that payments in the RES 2012 are contingent on the fulfillment of a 60% input volume limit for maize sourced inputs and a minimum of 35% external utilization of heat. Bonus payments for the RES 2012 differentiate between two input classes (BMWI 2012).

$$V_b \geq \sum_i X_i \tag{5}$$

$$V_b \leq I_{\mathrm{b}} * \beta_b * \phi \tag{6}$$

where V_b is the net-volume of the fermenter, X_i is the biomass input, I_b is the biogas inventory, β_b is the maximal net-volume and ϕ is the defined input reduction level.

The continuous biogas production is contingent on favorable biological and chemical conditions for the bacteria culture in the fermenter (Mulat et al. 2016). A measure to maintain such conditions for the bacteria is the digestion load. The digestion load is determined by the organic dry matter content in the fermenter per day relative to the volume of the fermenter expressed in equation (7). Recommended levels for the digestion load are given by literature and added as a restriction in equation (8)

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[5] The model assumes that the density of manure and all silage inputs is equal to 1 t/m^3 in the fermenter. (KTBL, 2013: 252).

(KTBL 2013; Fachagentur für Nachwachsende Rohstoffe e.V. 2013). Parameters applied in the production process can be seen in Appendix 2.1, 2.2 and 2.3.

$$\Delta_b = \frac{\sum_i (X_i * p_i)}{\beta_b} \tag{7}$$

$$\Delta_b \leq I_b * \gamma_b \tag{8}$$

where Δ_b is the digestion load, X_i is the biomass input, p_i is the dry matter content of each input, β_b is the maximal net-volume, I_b is the biogas parts inventory and γ_b is the maximal digestion load.

Economic part

The subsidies received for electricity from a biogas plant depend on the RES. The RES amendments differ with regard to requirements for total or partial bonus payments. Further, the payments can be subdivided into FITs and direct marketing premiums, the latter granted if electricity is sold on the spot market. The payments for FITs in the model reflect sliding scale prices as defined in the legislation (BMWI 2009), i.e. for the first 150 kW of electricity produced, the operator receives the payment for a 150 kW biogas plant and for the electricity produced between 150 kW and 500 kW the lower payment for a 500 kW plant. Furthermore, payments depend on the composition of the agricultural biomass used. Non-agricultural sources, which play a minor role overall, are not considered. For the RES 2009, it is assumed that 35% of the heat is utilized and all inputs are biomass based. Thus, the payments include a base rate, the Combined-Heat-Power-bonus (CHP-bonus), the NawaRo-bonus[6] and additionally the manure bonus if the manure input restriction described in the technological part is met. The RES 2012 payment structure includes the base rate and additional bonus payments based on the input specific electricity outputs. The payment structure of the FITs is shown in equation (9) and shows exemplary the payment structure of the RES 2012 with differentiated input classes.

$$\begin{aligned} R_{fit} &= \sum_b \sum_e \sum_{ic} Y_{ic,b} * \rho_{b,e} \\ &+ \sum_b \sum_{ic} (Y_{ic_1,b} * \sigma_{ic_1,b} + Y_{ic_2,b} * \sigma_{ic_2,b}) \end{aligned} \tag{9}$$

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[6] The NawaRo-Bonus is added to the payment if all input are derived from renewable resources or manure (BMWI 2009 §27(4) – Anlage 2)

where R_{fit} is the revenue of FIT payment system, $Y_{ic,b}$ is the electricity output, $\rho_{b,e}$ are the FITs for electricity, $\sigma_{ic,b}$ is the bonus payments for both input classes.

The direct marketing payment structure is shown in (10). The revenue from direct marketing is based on the assumption that the electricity is sold during two differing price level periods each day. The high price levels are the monthly arithmetic average prices of the 12 hours with the highest prices and the low price levels are the monthly arithmetic average prices of the 12 hours with the lowest price levels based on the year 2012 at the EPEX Sport market (EPEX Spot 2015). The share determining the amount of sold electricity during high- or low-price levels is contingent on the degree of flexibilization and thus on the input reduction level. The market premium for flexibly produced electricity is calculated based on the applicable FIT for the biogas plant and depends on plant size, input mix and the initial RES as well as the market value, which is the monthly average electricity spot price of hourly contracts. Consequently, the revenue of direct marketing is determined by the amount of electricity sold during high price levels or low price with the respective spot price and the market premium as a subsidy. Further, the necessary FIT increase to achieve a certain given input reduction level is included in the payment structure.

$$\begin{aligned} R_{dm} = & \sum_{b}\sum_{e}\left[(\sum_{ic} Y_{ic,b} * \delta) * (\upsilon_{b,e} + \theta_h + \chi_e) \right] \\ & + \sum_{b}\sum_{e}\left[(\sum_{ic} Y_{ic,b} * (1-\delta)) * (\upsilon_{b,e} + \theta_l + \chi_e) \right] \end{aligned} \tag{10}$$

where R_{dm} is the revenue of the direct marketing system, $Y_{ic,b}$ is the electricity output, δ is the share sold during high price levels at the electricity spot market, $\upsilon_{b,e}$ are the market premium levels based on the applied FIT, θ_h and $\theta_l$are the average high h and low l EPEX Spot price levels, χ_e are compensatory FIT increases to achieve the desired input reduction.

The biogas module distinguishes between variable costs depending on production level and biogas plant size (11). The electricity production level determines the electricity consumption of the biogas plant itself, which is assumed to be externally purchased. Further, costs for purchasing substrate from external sources are accounted for. Variable costs for on farm produced inputs are determined by the cropping module and the economic section of FarmDyn and thus comprise opportunity costs of land, labor and the machinery park. Last, variable costs also include yearly costs for maintenance and repairs, insurance, and laboratory tests depending on biogas plant size.

$$C_b = Y_b * \iota * \tau + \sum_i (X_i * p_i) + m_b \tag{11}$$

where C_b are yearly variable costs for the biogas plant, Y_b is the electricity output, ι is the price for electricity, τ is the consumed electricity as share of produced electricity, X_i is the biomass input, p_i is the price for each biomass input, m_b are the costs for maintenance and repairs, insurance and laboratory analysis.

Model application and scenario design

We quantify the necessary increase in FITs for two German regions with high livestock and high biogas plant densities and related negative externalities. Each region is represented by a dairy farm operating a biogas plant as a farm branch (Table 2.1) (Thünen-Atlas 2014; Fachagentur für Nachwachsende Rohstoffe e.V. 2009). Farm I with a 500-kW-biogas plant represents a typical dairy farm producing biogas in North-West Germany. It has 80 hectares arable and 100 hectares permanent grass land, respectively, and maintains a 105-cow herd. Farm II, situated in Lower Franconia, is a smaller dairy farm with 60 cows and a biogas plant with a nominal power of 250 kW. It has 20 hectares arable and 60 hectares permanent grass land available.

The nominal power of the biogas plants is chosen to come close to regional averages (Scheftelowitz et al. 2014). Both farms use 35% of engine heat, corresponding to the required minimal heat utilization of the RES 2012 amendment.

Table 2.1: Case study farms

	Unit	Farm I		Farm II	
Initial amendment		RES 2009	RES 2012	RES 2009	RES 2012
Construction Year	*[year]*	2009	2012	2009	2012
Application Year	*[year]*	2015		2015	
Nominal Power	*[kW]*	500		250	
Arable land	*[ha]*	80		20	
Grass land	*[ha]*	70		60	
Cows	*[count]*	105		60	
Average Working Unit	*[count]*	4.5		3.5	

Source: Farms constructed based on data from (Fachagentur für Nachwachsende Rohstoffe e.V. 2009; Thünen-Atlas 2014)

As the model does not yet entail the possibility to hire additional workers, farm family work units are set to a realistic but non-binding level. We assumed that unused labor can work off farm on an hourly basis for a wage of 6 €/hour. This assumption is based on a sensitivity analysis in which we found that already slight increases in hourly wages to 8 €/hour and the assumed milk price of 32 cents per kg, the dairy branch of the farm was discontinued. KTBL (2014) calculates for example farms with 64 and 120 dairy cows at a milk price of 36 cents per kg considerable losses when full costs are considered and labor is remunerated at 17.50 €/hour. Calculating the remuneration residually assuming full cost coverage yields implicit returns of around 3.60 €/hour (60 cows) and 9.75 €/hour (120 cows). Considering that our assumed milk price is with 32 cents per kg somewhat lower while full investment costs are not considered over the two decades, the price of 6 €/hour found in the sensitivity analysis seem to fit to the KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V.) data set, which is the main data source of the FarmDyn model.

The farmers' investment in biogas plants is made prior to the simulation as shown exemplary for the RES 2012 in Figure 2.1. At the start of the simulation the farm has the option to either remain in the initial RES, contingent on the construction year, or to switch to a new RES with direct marketing and reduced input. We determine the required FIT for a certain input reduction level by increasing the subsidy at the beginning of the simulation in 2015 until the farmer opts for the path with the new RES. After opting for the new RES, the farmer will continue to produce electricity until the end of the guaranteed subsidies in 2032, unless he decides not to reinvest in machinery parts with a lifespan smaller than 20 years.

We consider two alternative construction time points for the biogas plants of each farm which determines the applied initial RES: the RES 2009 for the construction year 2009 and the RES 2012 for the construction year 2012. The two different payment schemes and their compositions are shown as examples for the RES 2009 amendment for Farm I in Figure 2.2.

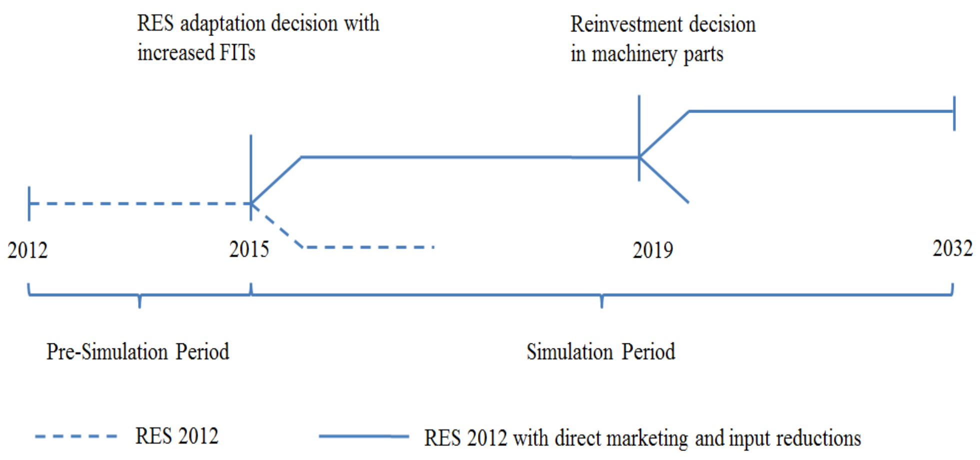

Figure 2.1: Strategic decision implementation in FarmDyn

Source: Own depiction

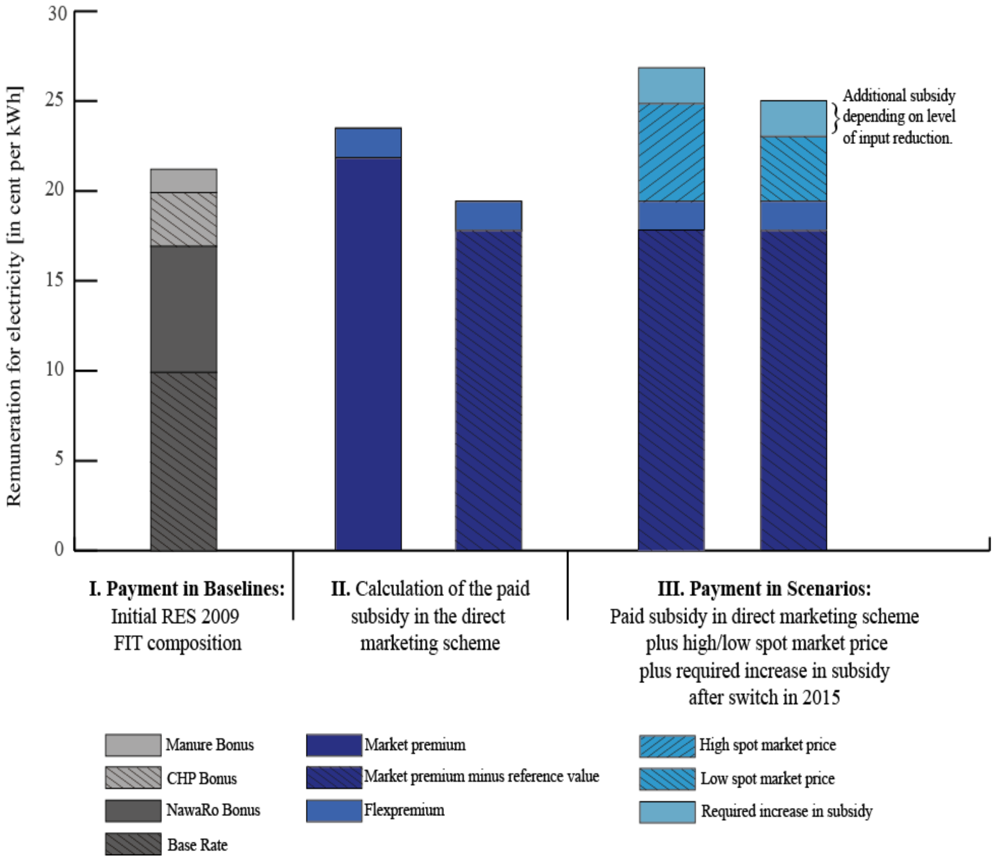

Figure 2.2: Composition of payment scheme in the baseline and the scenario – Farm I RES 2009 amendment

Source: Own depiction using data from KTBL (2013)

The payment in the baseline (I) shows the composition of the initial FIT in the RES 2009. The initial FIT determines the level of the market premium and serves as the basis for the calculation of the subsidy (II). The market premium minus the reference value, which is given by the monthly average spot market price, and the flexibility premium sum up the subsidy received by the biogas operator in the direct marketing scheme. The payment in the scenarios (III) are thus the initial subsidy plus the received spot market price plus the required increase in subsidy for a given input reduction level. In the study at hand, we consider input reduction levels from 5% to 50% in steps of 5%. The payment schemes of the four scenarios and their baselines are shown in Figure 2.3. The subsidy increases reflect risk neutral behavior, i.e., sole changes in costs and revenues. Figure 2.3 below shows that under flexible energy production the vast share of the payments is still made of guaranteed subsidies. Thus, we conclude that a further increase in subsidies to cover a risk premium when considering risk adverse behavior is probably small.

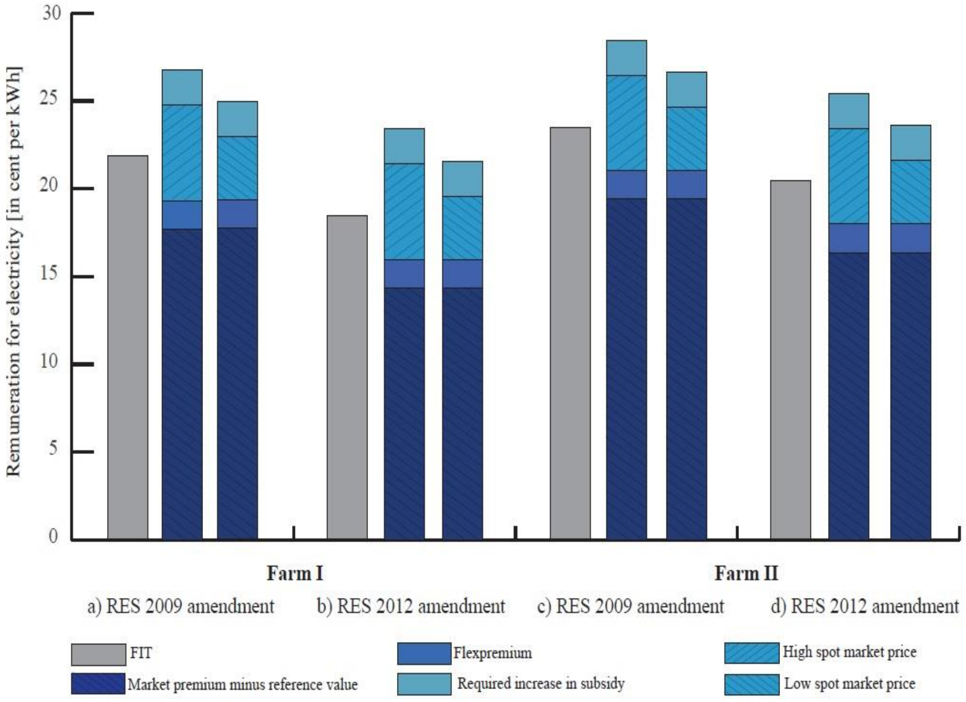

Figure 2.3: Composition of payment scheme in baselines and scenarios for all four scenarios

Source: Own depiction using data from KTBL (2013), EPEX SPOT (2015)

2.3 Results and discussion

2.3.1 Farm management: environmental and economic implications

The simulations show that purchased maize is the primary biomass source reduced in all scenarios when average power output is decreased (cf. Figure 2.4). Legislation limits the flexibility of the farmer in the input mix considerably: in order to receive the sizable manure bonus in the RES 2009, 30% of input mass must consist of manure. Furthermore, the RES 2012 prescribes that silage maize cannot exceed 60% of input volume, such that farmers have to add other feedstocks; for the farms with grasslands considered in the paper, that is grass silage. That result reflects the fact that permanent grass land, in accordance with the German implementation of the Greening component of the CAP 2014 (European Commission 2013; BMWI 2014; BMEL 2014), cannot be converted to arable land in the model without compensation areas, making grass silage profitable as a feedstock for the farms under investigation. Consequently, reducing the average power load of the engine translates into a reduction of the bought silage maize. Thus, the share of grass silage in the fermenter increases with the simulated reduction of the average fermenter load.

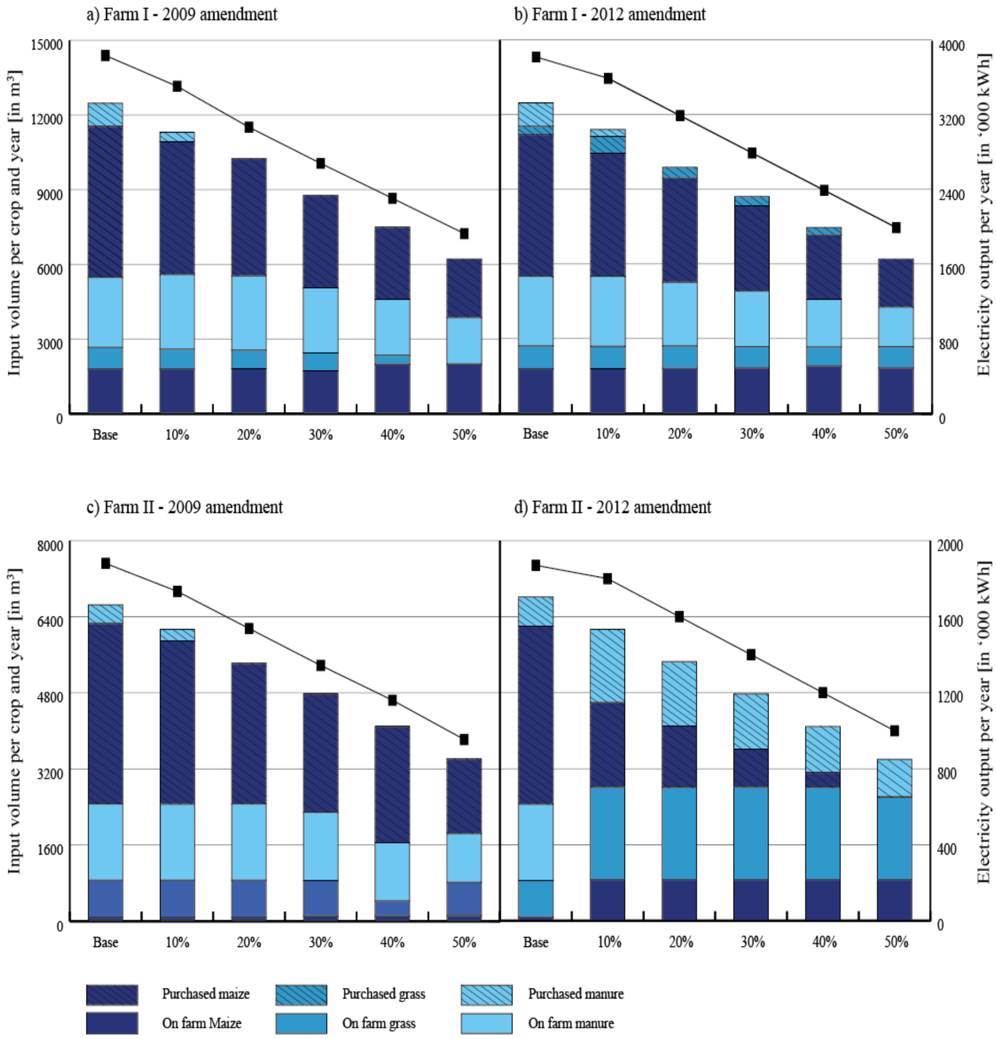

Figure 2.4: Input volume and composition for input reduction levels

Source: Own calculation with FarmDyn

This tendency of reducing maize input and increasing the share of grass silage can alleviate negative environmental externalities related to biogas production such as potential nutrient leakage, soil run-off and pesticide input. Further, negative effects on biodiversity could be reduced especially in regions with high shares of maize (DeStatis 2014; Sachverständigen Rat für Umweltfragen 2007; Deuker et al. 2012; Bunzel et al. 2014). However, we cannot exclude that maize bought into the farm does not find another demand, e.g. as feed in livestock production in other farms, such that the environmental benefit could be even zero.

Several authors recognized positive effects of biogas digestates with respect to emission reduction and ecological benefits for soils compared to untreated slurry (Amon et al. 2006; Vaneeckhaute et al. 2013). However, the regions under investigation are characterized by both high biogas plant and animal densities and thus experience high nitrogen (N) and phosphor (P) loads (Wüstholz et al. 2014) with undesired environmental threats such as eutrophication and contaminated groundwater. That fact is partially due to the lack of accounting plant based digestate in the N application limit of the German Fertilizer Directive (BMELV 2007) and the lack of enforcement of the allowed maximum N surplus on farm (Osterburg und Techen 2012).

For the larger Farm I, all simulated input reduction levels under both amendments do not entail any significant farm management changes with respect to cow herd size and cropping pattern as seen in Table 2.2. Only a relatively minor increase in off farm work can be observed, otherwise used in biogas production. The smaller Farm II, however, experiences a drastic change in its farm management under the RES 2012 amendment. With already a 10% input reduction, the farm almost completely withdraws from dairy production and only concentrates on biogas production on farm and distributes 90% of its labor force to off farm work. Using the manure from the herd and economies of scope and scale from producing feedstock, both for the cows and the biogas plant, render a smaller dairy herd attractive as long as the biogas plant is fully utilized. Once feedstock and labor demand from the biogas plant drop, especially indivisibilities in labor use render it attractive to work mostly off farm. The withdrawal of the dairy branch can also be seen in the input mix of the fermenter in which primarily on farm produced grass silage is used. Even if farms, which give up on dairy farming, could alleviate some negative environmental effects, a widespread withdrawal from dairy farming might trigger far-reaching negative economic consequences at regional level, e.g. on employment and in up- and downstream industries such as dairies (Emman et al. 2014).

Table 2.2: Case study farms: Key farm characteristics in baseline and after a 50 percent input reduction for all scenarios

	Unit	Farm I			
		RES 2009		RES 2012	
		Base	50% Red.	Base	50% Red
On Farm Work	*[hours]*	9678	8323	9658	7902
Off Farm Work	*[hours]*	71	1117	91	1597
Cows	*[count]*	105	105	105	105
Grassland used for dairy	*[ha]*	33,6	60	34.1	34.2
Grassland used for biogas	*[ha]*	26.4	0	27.9	26
Arable land used for dairy	*[ha]*	39.2	34.3	39.6	38.8
Arable land used for biogas	*[ha]*	40.8	45.7	40.4	41.2
		Farm II			
		RES 2009		RES 2012	
		Base	50% Red.	Base	50% Red
On Farm Work	*[hours]*	5921	5524	5911	1228.7
Off Farm Work	*[hours]*	2578	2975	2588	7271
Cows	*[count]*	60	60	60	0
Grassland used for dairy	*[ha]*	34.2	36.8	46.13	0
Grassland used for biogas	*[ha]*	23.9	21.4	10.14	53
Arable used for dairy	*[ha]*	18.0	17.1	17.84	0
Arable used for biogas	*[ha]*	1.7	2.5	1.86	19.7

Source: own calculation with FarmDyn

2.3.2 Additional required subsidy for decreased biomass demand

A more demand-driven electricity production could allow a biogas operator to reap benefits of increasingly volatile electricity prices on the EPEX SPOT market (Paraschiv et al. 2014), while contributing to a more stable electricity grid in the energy transition. Hochloff und Braun (2014) found that with optimal direct marketing of produced electricity the participation on the electricity spot market is profitable under the subsidy scheme of the RES 2012. Barchmann und Lauer (2014) showed that an increase of 100% of the installed capacity of the power engine is the most beneficial option to switch from a FIT based payment scheme to direct marketing scheme. In contrast, with our proposed biogas plant setup in which the average fermenter load and electricity production is reduced, results show that sizeable increases in FITS are necessary to let farmers switch to flexible marketing. The additional subsides per unit of electricity needs to cover to a larger extent the reduced returns to farm own factors due to the output reduction. These results are consistent for both farms and RES amendments considered. Figure 2.5 shows that the RES 2009 amendment requires the highest increase in FITs.

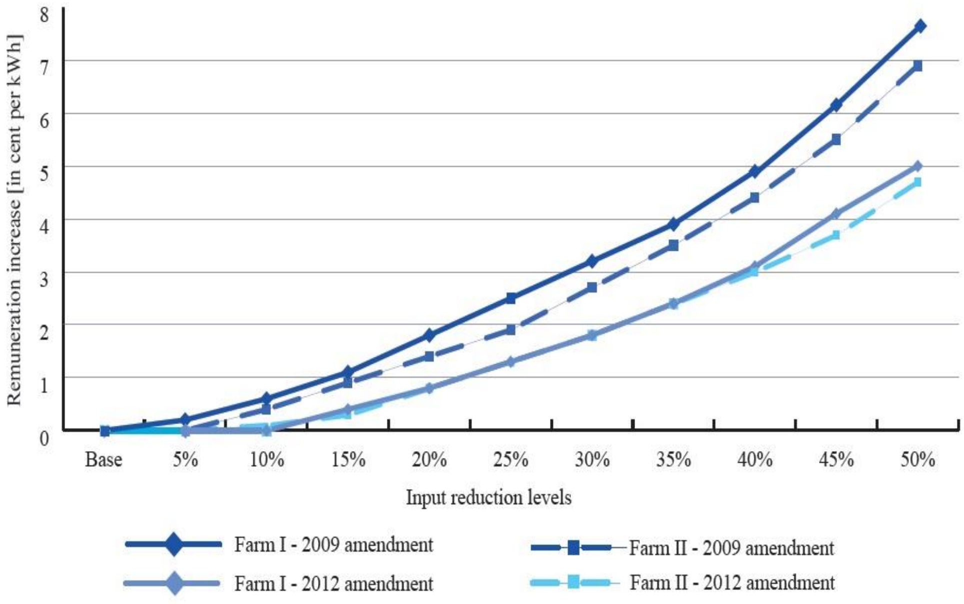

Figure 2.5: Necessary increase in FITs for different input reduction levels

Source: own calculations with FarmDyn

The additional payments for a 10% to 50% input reduction range from 0.6 up to 7.4 Euro cents per kWh, respectively. The lowest additional subsidy has to be paid in the RES 2012 amendment for Farm II. However, at an input reduction of 50% the required increase in FITs is still 4.7 Euro cents per kWh, i.e., 135% of the average market value of hourly contracts at the EPEX SPOT prices in 2012 (EPEX Spot 2015). As electricity produced by biogas plants already have the highest production costs among renewable energies (Kost et al. 2013) such an increase in subsidies would be politically hard to enact. In particular, additional subsidies paid to producers of renewable based electricity are directly driving up consumers’ bills.

However, this study only investigates direct marketing based on participation on the EPEX Spot market. Other marketing options, such as secondary control reserves and minute reserves (Thrän et al. 2015), might generate higher per unit revenues and thus require lower additional subsidies for the proposed biogas plant setup. In addition, shifting from the base load setup to a more flexible setup can lead to a reduction in GHG emissions as biogas is competing against flexible fossil fuels, such as coal-fired and gas-steam power stations, instead of the average energy mix (Lauer et al. 2017).

2.4 Summary and conclusion

Various studies have shown that the expansion of biogas plants with the primary use of energy maize in Germany poses threats to the environment (EEA 2007; Osterburg und Röder 2013) as well as for existing agricultural production and its value chains (Rauh 2010; Emman et al. 2012; Emman et al. 2014). Simultaneously, the German government tries to foster flexible electricity production for biogas plants in order to offset fluctuating electricity generation of wind and solar energy and thus stabilize the electricity grid (Strunz 2014). While most recent studies on flexible electricity production had a focus on biogas setups with the highest economic viability (Barchmann und Lauer 2014; Hochloff und Braun 2014; Hahn et al. 2014), we proposed to have an extended view and to integrate environmental and agricultural sector concerns into the biogas setup by reducing biomass demand.

In this investigation, the aim was to quantify the required additional subsidies for two typical farms operating biogas plants under the RES to switch from continuous biogas production to flexible marketing. For this purpose, we used the highly detailed single farm model FarmDyn in combination with a newly developed biogas module. The flexible electricity load is assumed to be available from using the existing fermenter as gas storage by reducing the average fermenter and engine load. Our results indicate that even for moderate levels of flexible load such as 30%, sizeable additional subsidies of 1.8-3.2 ct/kWh, i.e., around 52% to 91.9% of typical average spot prices, would be required to let farmers switch to flexible marketing.

The required changes in farm management are quite small, as the main impact are reduced purchasing of feedstock for the biogas plants. Such a reduction would be desirable as the main feedstock of biogas plants is energy maize whose cultivation is linked to negative environmental externalities such as increased soil erosion, loss of biodiversity and increased nutrient loads. Equally, reducing feedstock demand would ease pressure on land markets and maintenance of permanent grass land.

We conclude that the consequences for Germany’s farming sector and the environment of a flexibilization of existing biogas plants are probably positive and a realization based on using existing fermenters as additional gas storage relatively simple from a technical viewpoint. Enforcing this option is, however, unlikely as the legislation under which existing plants were erected guaranteed subsidies for 20 years. We therefore see a wide-spread application as rather unlikely due to relatively high additional subsidies required to let farmers opt for it and the already considerable share of costs for renewable energy in the electricity bill of German households.

However, being limited by the computational restrictions in the modeling framework of this study, the results have to be viewed with caution as aspects such as risk attitude or multiple objectives could not be implemented. Further, the study focuses on the participation on the electricity spot market, while providing positive or negative balancing energy might be another possible payment opportunity for biogas plant operators in future studies.

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Chapter 3

Improved assessment of regional manure transports using a bi-level programming calibration approach

Abstract

Legal restrictions for manure application and high livestock densities force farms to export excess manure. In Germany, already sizeable intra- and inter-county manure exchanges are expected to further expand due to revised national fertilizing regulations. We present an approach to quantify impacts of stricter policy measures for the application of biogas digestate and animal manure in nitrate pollution hotspots (NPHs) on manure transports between 396 communes in the federal state of North Rhine-Westphalia (NRW). A bi-level programming model calibrates an spatial price equilibrium (SPE) model to observed manure transports under the behavioral assumption of transaction cost minimization. Compared to an uncalibrated SPE model, it yields an improved fit by recovering both the predominant short-distance transports but also long-distance transports. The analysis of scenarios with the calibrated model showed that stricter measures lead to a broader distribution of nitrogen (N) in the landscape. This directly affects associated policies which foster long-distance manure transports and can lead to pollution swapping, contradicting the initial aim of the revised fertilizer legislation. We consider the findings of interest as they highlight the advantage of using the novel bi-level calibration approach when analyzing policy impacts on the manure market.

Keywords: Bi-Level Programming, Spatial equilibrium model, Environmental Regulations, Manure Transport, Nitrates Directive

3.1 Introduction

Livestock manure is a valuable source of crop nutrients and organic matter; but it is linked to manifold negative externalities when not adequately handled. Continued increases in livestock densities on many farms let nutrient imports from feed concentrates exceed the nutrient absorption capacity of their land. The lost link between land and livestock provokes high spatial nutrient concentrations with negative impacts, especially on aquatic ecosystems (Naylor et al. 2005; Steinfeld et al. 2006). In Europe, this development can be seen in the Netherlands, Flanders, Brittany, Denmark and northwest Germany (Kronvang et al. 2008; van Grinsven et al. 2012; Umweltbundesamt 2014). In Germany, this trend was amplified by the introduction of subsidy schemes which remunerated the co-fermentation of manure and plant-based inputs in biogas plants. As farms typically import larger feedstock shares for their biogas plants from other farms, the nutrient pressure on their farmland increases if no other alleviating strategies are applied such as disposing manure off-farm or reducing inorganic fertilizer use.

In 1991, the European Union introduced the Nitrates Directive (ND) (91/676/EEC) as an essential part of the Water Framework Directive (2000/60/EC). It aims to protect ground and surface water from nitrate (NO_3^-) stemming from agricultural sources, as well as to improve the quality of already polluted water bodies within the Member States (European Commission 1991). The ND sets a 50 mg NO_3^- l^{-1} standard for good water quality and recommends Codes of Good Agricultural Practice for farmers to mitigate NO_3^- emissions into the aquatic ecosystem. In Germany, the ND is implemented as the national FO based on a command-and-control approach for farms (BMEL 2006).

Since 2012, several reports by German authorities indicated that many ground water bodies exceed the 50 mg $NO_3^- l^{-1}$ standard, even with increasing trends. These NPHs, as defined by each federal state, often occur in regions with high livestock and biogas plant densities as often found in the north western part of Germany. As a consequence of the development in these NPHs, the European Commission referred Germany to the EU’s Court of Justice for insufficient implementation of the ND (European Commission 2016). The German government reacted by implementing a revision in 2017, which again was deemed inadequate to meet the ND targets leading to another FO which came into force in 2020. Stricter measures in these amendments included, for example, the accounting of plant-based biogas digestate and the reduction of organic and inorganic N use determined by mandatory fertilizer planning by 20% (BMEL 2020).

To comply with restricting fertilizer measures, farmers have a range of adaptation strategies which help to close the nutrient cycle at farm- and regional levels. These comprise, for example, switching to N-reduced feeding, reducing livestock numbers, or decreasing biogas plant load at farm-level and exporting excess nutrients to other farms at regional level. Transporting manure to other farms has been identified as the most prominent compliance strategy under the FO 2007 for intensive livestock farms (Kuhn et al. 2019b).

Literature has quantified and assessed economic and environmental impacts of manure exchanges, both at the level of individual farms and administrative units. Nutrient cycles and impacts on indicators such as eutrophication, acidification, climate change, and non-renewable energy use were extensively studied for farm-to-farm flows (Lopez-Ridaura et al. 2009; Kuhn et al. 2018). Other studies analyzed minimized manure transport costs under environmental and economic restrictions based on Geographic Information Systems (GIS) analysis (Paudel et al. 2009; Kang et al. 2008). At the administrative unit level such as communes, research considered both economic impacts of manure transports such as reallocation costs (Aillery et al. 2009; van der Straeten et al. 2010; Auburger et al. 2015) and environmental impacts such as the level of CO_2 emission (van der Straeten et al. 2011; Willeghems et al. 2016).

Most of these studies account for manure management policies as driving factors for manure transport, such as the national implementation of the ND, ex-post (Lopez-Ridaura et al. 2009; van der Straeten et al. 2011; Willeghems et al. 2016) or evaluate potential revisions ex-ante (Auburger et al. 2015; Kuhn et al. 2018). Further, some authors analyzed the emergence of manure markets at the regional level against the background of such policies (Lauwers et al. 1998; van der Straeten et al. 2011; Willeghems et al. 2016). In these studies, policy induced manure markets are depicted by SPE models which simulate cost minimized manure transports between aggregate agents which represent all farmers situated in the same commune. However, previous studies have neglected the step of calibrating their model to reproduce observed supply, demand, and bi-lateral exchanges; a modeling step which is stressed in literature about SPE models to be critical (Paris et al. 2011; Wieck et al. 2012) .

This study aims at contributing to existing literature twofold. First, it develops a bi-level model which calibrates a transaction cost minimizing SPE model to improve the assessment of changes in this widely applied model type to depict manure transports. The new method is evaluated by comparing baseline and policy simulation results between a calibrated and uncalibrated version. Second, it analyzes the impact of two key changes in the German FO, namely, accounting for N from plant-based biogas digestate in the 170 kg N ha^{-1} application limit from the FO 2017 (*biogasD),* and a reduction of the allowed maximum manure N application limit from 170 to 150 kg N ha^{-1} (*nitrogenRed1*) and 130 kg N ha^{-1} (*nitrogenRed2*) in NPHs based on the FO 2020.

The German state of NRW is chosen as case study region due to considerable manure transports. Official statistics (LWK NRW 2018b) report that 18.15% of all N stemming from livestock, biogas digestate, and imports from the Netherlands and other German states is subject to inter-county transports, whereas intra-county transports are even larger with 45% of all N contained in manure and digestate being transported between farms. The applied calibration methodology and insights into impacts of fertilizer regulation measures of the German ND implementation on manure transports is of broader interest as similar measures and considerable manure exchanges are found in many other countries.

The remainder of this chapter is structured as follows. Next, the methodological section presents the conceptual framework of the SPE with its underlying behavioral assumptions, followed by the concept of the bi-level estimation, including its mathematical formulation. Section 3.3 discusses important characteristics of our case study region NRW with respect to manure transports and motivates the selection of the chosen policy measures. Results are then presented for the calibrated and uncalibrated model and for simulated impacts of policy changes on manure transports. Lastly, results are discussed followed by conclusions.

3.2 Methodology

The applied model is based on a bi-level model which is partitioned into an upper and lower-level problem. The upper-level problem minimizes the squared normalized differences between observed and estimated N transports between counties. The lower-level problem is a SPE model which minimizes total transaction costs where the transaction costs between communes are controlled by the upper-level problem. The SPE is used after the calibration and in the uncalibrated model version for counterfactual analysis. The section begins with showing the relevant assumptions about manure trade in the SPE, followed by the presentation of the bi-level estimation approach and its mathematical formulation. Finally, the data used in this model is presented.

3.2.1 Conceptual framework of manure transport

In our model, we use the aggregated version of manure in tons of N. Available transport data gives only information about mass flows in tons of N, hence, we cannot account for different manure types (dairy, pig, poultry etc.) and their respective nutrient contents, nor can we simulate competition between organic and inorganic fertilizer. In the remainder of this paper, manure is defined to comprise both manure from livestock and plant-based biogas digestate, if not specifically mentioned as animal manure or digestate.

Each commune acts as an aggregate farmer with respect to managed acreage, to N excreted by his herd and to legal nutrient application thresholds. SPE models assume rational behavior, i.e., if farmers are legally obliged to export excess nutrients, they comply in a cost minimal way. Hence, simulated transports are always cost minimal. Accordingly, a commune depicted as an agent in a SPE can be a net-exporter or net-importer of N or refrain from trading, but cannot simultaneously import from and export to other communes, as netting out such counter trade saves costs (Takayama und Judge 1971).

The model assumes further that, first, the aggregated farmer in each commune complies with the law, and that exporting farmers in each commune have to carry the costs of manure transport to the accepting farmer’s plot. This reflects the usual contractual agreement in the case study state NRW. The assumption of cost minimal behavior implies that farmers will apply manure on their fields up to legal limits even if exceeding crop needs in order to save transaction costs.

In NRW, manure transport is either organized bilaterally between the exporting and importing farmer or by specialized nutrient exchange companies. The latter are pooled in NRW under the organization “Nährstoffbörse” (“nutrient exchange”) to reduce transaction costs and to facilitate long distance manure exchanges (Nährstoffbörse 2019). As our model operates at communal level, manure trade in the model can be understood as organized by companies which act as spatial arbitrageurs, with one being located in each commune. Transaction costs are assumed to depend on distance and transported manure quantity, considering additional per unit costs of loading and unloading.

The data for N flows, application and excretion are available at county level, only, see Section 3.2.4, while estimates on livestock numbers and crop acreages are available per commune. We estimate the missing data on N application for each commune by regressing the reported application rates at county level based on available land and livestock figures using ordinary least square, and then derive commune estimates. Commune estimates are subsequently scaled to exactly exhaust the observed county data.

3.2.2 Bi-level estimation and random search algorithm

The estimation approach for transaction costs of manure transports builds on Heckelei und Wolff (2003) and Jansson und Heckelei (2009) by using a bi-level estimation approach which uses the first-order conditions from cost-minimizing behavior as estimation (in-)equalities (Figure 3.1). The model is written in the programming language General Algebraic Modeling System (GAMS) and uses the JAMS solver for Extended Mathematical Programming models developed by Michael Ferris (Ferris et al. 2009; GAMS Development Corporation 2019).

Each bi-level programming approach comprises an upper and lower optimization problem. The JAMS solver reformulates the lower problem in its Karush-Kuhn-Tucker (KKT) first order conditions and passes it together with the upper optimization problem to a non-linear programming (NLP) solver, here CONOPT4 (Arne Drud n.d.). The many KKT inequalities imply a non-convex solution space which comprises many local minima. CONOPT4, as a gradient based solver, is extremely robust and efficient in solving large-scale NLP problems. However, it cannot guarantee global optimality if the overall problem is not convex and stops once it finds one of the local minima. Accordingly, a random search algorithm is added which repeatedly solves the reformulated bi-level problem. In between the repeated solves, either the estimated flows or estimated parameters are perturbed to serve as new starting values until a better solution is found. As the bi-level problem is highly non-linear and exhibits several thousand variables, solving for a single local minimum can take up to five minutes on a fast computer with four cores. Due to the high dimensionality of the problem, the random search is repeated several hundred times. To improve the model results, we tuned the algorithm by changing the way the perturbations are defined until we found a compromise between provoking very large infeasibilities in many cases and staying too close to the current best solution.

So-called global solvers such as BARON (Sahinidis 2015) and ANTIGONE (Floudas und Misener 2013) which claim to be able to find global solutions to non-convex problems were tested as alternatives. However, they typically failed to find even a single feasible solution. This outcome might reflect that the problem has a high number of unknown parameters with many non-convex relations. It features around 50,000 variables and 100,000 equations with 420,000 non-zeros of which 120,000 are non-linear. Thus, it is larger than any of the non-convex test problems for global solvers found for instance in the “Library of Mixed-Integer and Continuous Nonlinear Programming Instances” (Vigerske 2019).

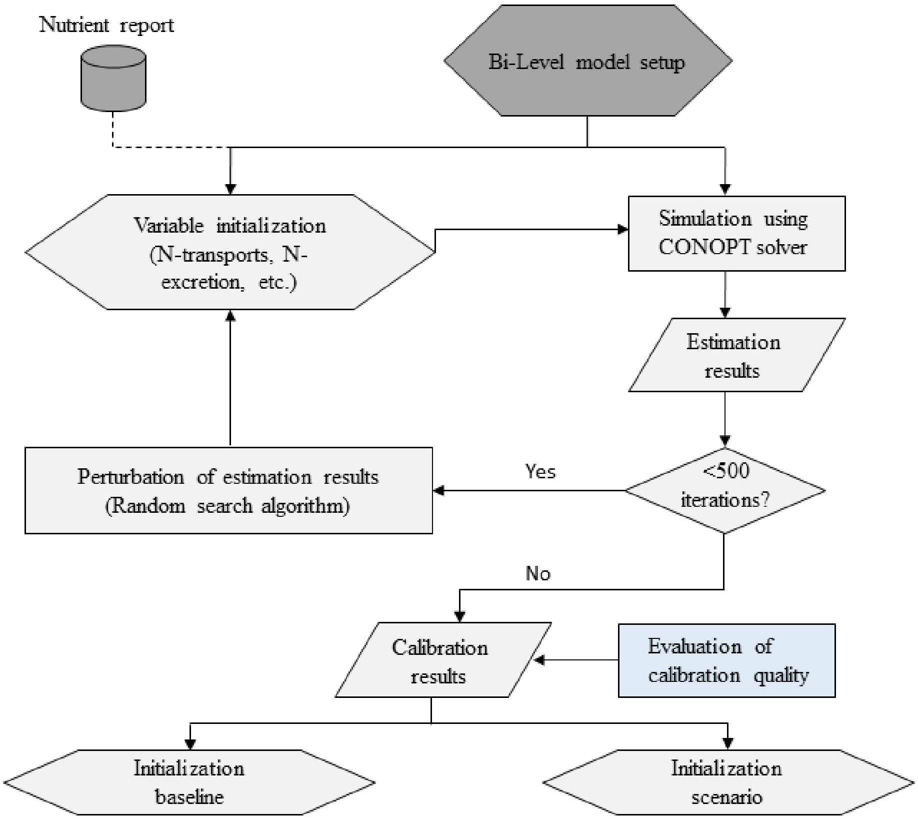

Figure 3.1: Bi-level model set-up and estimation procedure

Source: Own depiction

3.2.3 Mathematical formulation of the bi-level problem

The upper problem minimizes mean squared normalized differences between bi-laterally observed $of_{co,co'}$ and estimated N transport flows $f_{co,co'}$ between counties *co* (1). For that purpose, it controls parameters which define the transaction costs governing the optimal decisions in the lower problem where transaction costs are minimized. Note that the estimator can and will also introduce manure flows between pairs of counties where $of_{co,co'}$ is zero, i.e., no manure exchanges are observed. Accordingly, a normalization of all differences between estimated and observed flows by observed ones will provoke divisions by zero. This motivates the introduction of the *eps* threshold which was chosen as one ton. As observed flows are usually at least 100 tons and generally much larger, using 1 ton for unobserved ones introduces a high penalty for introducing unobserved flows. Equation (2) aggregates manure exchanges between communes to exchanges between counties which enter the objective function (1). The transports between communes are determined by the lower-level problem depicting cost minimal exchanges at given parameters, whereas the transports between counties enter the objective which drives the parameter choice. The model assumes that imports into NRW (3a) and exports out of NRW (3b) are fixed to the sum of observed flows. The estimated transaction costs per unit between each pair of communes are given in (4). The per unit transaction costs related to distance are expressed in linear, square, and square root terms. This functional form assures a convex problem for the solver to find local optimality.

$$min \qquad fit \;= \textstyle\sum_{co,\,co'} \left[\frac{of_{co,co'} - f_{co,co'}}{of_{co,co'} + eps}\right]^2 \qquad \text{,co and co' } \in \text{CO} \qquad (1)$$

$$s.t. \qquad f_{co,co'} = \sum_{c\_co,\, c'\_co'} f_{c,c'} \qquad \text{,co and co' } \in \text{CO, c and c' } \in \text{C} \qquad (2)$$

$$\sum_{co} of_{co,co',i} = \sum_{co} f_{co,co',i} \qquad \text{,co and co' } \in \text{CO} \qquad (3a)$$

$$\sum_{co} of_{co,co',o} = \sum_{co} f_{co,co',o} \qquad \text{,co and co' } \in \text{CO} \qquad (3b)$$

$$transC_{c,c'} = \; tcD * d_{c,c'} + tcS * {d_{c,c'}}^2 + tcR * \sqrt{d_{c,c'}} \qquad \text{, c and c' } \in \text{C} \qquad (4)$$

In the problem above, *fit* is the sum of the squared relative deviations, f are the estimated manure transport flows in metric tons, of indicate observed transport flows at county level, *eps* is equal to 1 metric ton, *co* is a county from the list of all counties *CO* and *c* is a commune from all communes *C*, *c_co* are the connection of communes *c* belonging to a certain county *co*, *c', co'* and *c_co'* depict all other communes, counties, or affiliations of communes to counties in an equation, *i* refers to import flows from neighboring countries and states, *o* are the corresponding export flows to neighboring countries and states, *transC* are distance related estimated transaction costs per kg of N between pairs of communes, *tcD, tcS* and *tcR* are parameters describing distance *d* related N transaction costs per kg between pairs of communes (*D* = linear, *S* = quadratic, *R* = square root).

The lower problem depicts cost minimal handling of N at commune level allowing for exchanges between communes. It is reformulated in its KKT conditions by the

JAMS solver which serve as additional constraints to the upper-level problem in the estimation. Variables indicated with a circumflex such as $\widehat{transC}_{c,c'}$ are free in the estimation procedure but enter as “fixed” and “given” in the lower-level problem in the simulation of the baseline and scenario. A list of variables, parameters and sets with their respective affiliation as decision variables in the upper and lower problem is given in Appendix 3.1. The objective function of the transaction cost minimization problem (5) encompasses the transaction costs of inter-commune manure exchanges at given bi-lateral per unit transaction cost $\widehat{transC}_{c,c'}$, as estimated by equation (4) in the upper level. The $\widehat{tcH}$ accounts for quantity related handling costs in the model. The remainder of equation (5) introduces marginal revenue from using N in the respective commune. Constraint (6) depicts the mass balance for manure in each commune; the excreted quantity q_c plus imports from other communes and other sources (biogas $of_{c,b}$, sewage $of_{c,s}$, out of state$of_{c,b}$) must be equal to exports and what remains in the commune s_c i.e. is applied to fields in the communes. Constraint (7) reflects the legally binding application rate (*maxApplRate,* 170 kg ha^{-1} in the baseline), discounting N from biogas fermenter digestates under the old FO 2007.

$$min \quad transAC = \sum_{c,c'} \left(f_{c,c'} * \widehat{transC}_{c,c'} + f^2{}_{c,c'} * \widehat{tcH} \right) + \sum_{c} \hat{p}_c * s_c \qquad \text{, c and c'} \in \mathrm{C} \qquad (5)$$

$$s.t. \quad q_c + \sum_{c} f_{c',c} + of_{c,b} + of_{c,se} + f_{c,i} = s_c + \sum_{c} f_{c,c'} + f_{c,o} \qquad \text{, c and c'} \in \mathrm{C} \qquad (6)$$

$$s_c - of_{c,b} \leq ha_c * maxApplRate_c \qquad \text{, c and c'} \in \mathrm{C} \qquad (7)$$

Where $transAC$ are minimal transaction and transportation costs, $\widehat{transC}$ are distance related estimated transaction costs per kg of N between pairs of communes, $\widehat{tcH}$ are quantity dependent handling costs, $\hat{p}_c$ are marginal costs or revenues, q is the excreted manure quantity net of storage and application losses in tons of N, and *s* is the amount of N remaining in a commune. The circumflexed symbols depict data or estimated parameters which are exogenous for decisions in the lower problem. The *se*, and *b* relates to nutrient imports from sewage, and biogas plants, respectively. Note that the diagonal elements of *f* are set to zero.

The uncalibrated model assumes that $\widehat{transC}$ is fixed at 1 Euro per kg and km and equal for each commune by neglecting price differences and thus different transaction costs between communes as in the calibrated model. As long as no differences in per unit transport costs between communes are introduced, the chosen level has no impact on simulated transport flows. It will only change total transaction costs.

3.2.4 Data base

In order to assess manure transport flows, we use data provided by the "Nährstoffbericht NRW" (nutrient report) prepared by the state government of NRW (LWK NRW 2014). It reports the amount of N and phosphorus (P) excreted by animals net of losses during storage, produced by biogas plants in form of digestates, stemming from sewage sludge and from imports as well as exports for each of the 53 counties (31 counties, 22 urban district counties) in NRW. Imports and exports are differentiated between country (Netherlands and Belgium), between German federal states (Lower Saxony and Rhineland Palatinate) and between each county within NRW. The imports comprise observations on bi-lateral nutrient exchanges between counties in NRW. As all values in the nutrient report only relate to N or P, we cannot distinguish between different livestock manures which, for instance, vary in water content and N:P ratio. Hence, we only model the N exchanged between administrative units. Thus, from now on we use manure and N sourced from organic compounds interchangeably. Data on agricultural land use at the commune level are taken from the Thünen-Atlas database (Gocht und Röder 2014), which is built upon farm structure survey microdata and country aggregates for activities (FDZ 2010), as well as GIS land use data (BKG).

In order to account for the existing road infrastructure of NRW, distances between communes are measured as driving distances in km as calculated by Google Maps route planner assuming transport by truck (Google n.d.). Thus, our distance matrix comprises 396 x 396 entries for distances between communes. These distances relate to the centroids of the administrative units and are hence only proxies. They could both be smaller in cases where the average distance between the manure storage of the delivering farmers and the accepting plots is close to the nearest border of the two units, and larger, when the opposite holds. On average, differences between the driving distance from the route planner and true ones are captured in the parameter which estimates transport costs per km driving distance between the centroids. In order to allow a model size capturing almost all transports, we excluded exchanges beyond 120 km.

In order to account for stricter measures linked to NPHs in the upcoming FO 2020, the model uses data on chemical conditions of groundwater bodies in NRW (LANUV 2020). Specifically communes, as the lowest administrative unit in the model, are defined as an NPH if more than 50% of the total land area is marked as an NPH.

3.3 Case study state and policy setup

3.3.1 Regional manure trade and nitrate vulnerable zones in North Rhine-Westphalia

The case study state of NRW shows distinct differences in its regional farming structure with livestock intensive regions in the northwest and other regions dominated by arable farms and extensive livestock. Due to favorable subsidies for the use of manure in biogas plants, investments in that sector are clustered in counties with high stocking rates. The four most livestock intensive counties hold 38.63% of all livestock, in total, while their agricultural area accounts for only 22.69% of the total agricultural land (DeStatis n.d.). They host 42.30% of all biogas plants representing 39.30 % of the installed electric capacity in 2016 (LWK NRW 2018a). In addition, NRW is neighboring livestock intensive regions of the Netherlands which export considerable amounts of N to German counties close to the border. The import of N from the Netherlands accounted for 8% of all N from agricultural sources in NRW in 2016 (LWK NRW 2018b). The combination of large livestock numbers, a high density of biogas plants and considerable amounts of manure imports from the Netherlands lead to high concentrations of N in the northwestern region of NRW (Figure 3.2a).

The distribution of exporting and importing counties is depicted in (Figure 3.2b). The counties with high animal and biogas plant densities show the highest net-export of N. Counties bordering the Netherlands show, despite a high animal and biogas plant count, net-imports of N from agricultural sources. The NPHs in NRW are clustered in the west and north of NRW (Figure 3.2c). The designated NPHs overlap with (1) livestock and biogas plant intensive counties, and/or with (2) counties with a large share of N imports from the Netherlands.

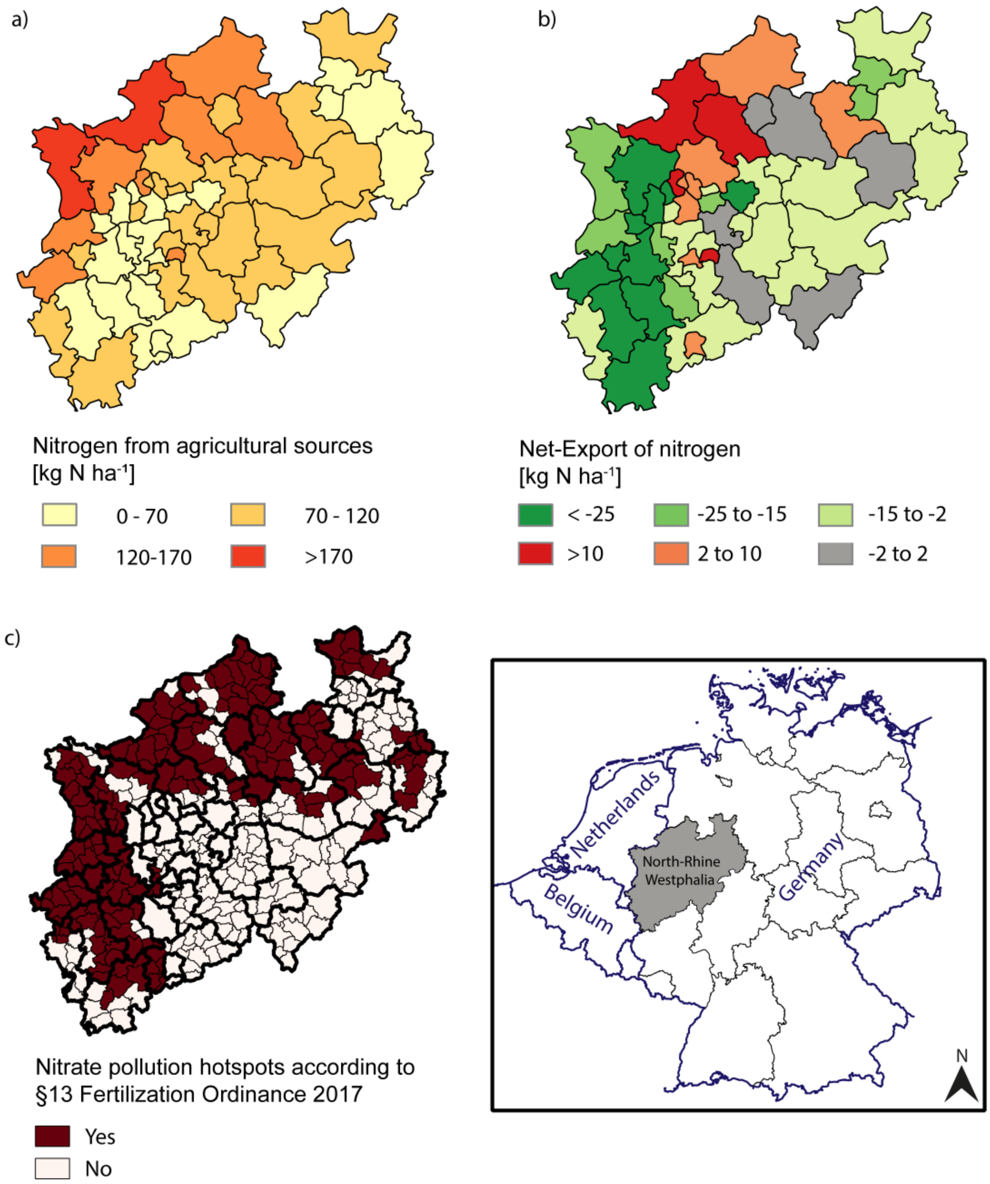

Figure 3.2: a) Allocation of N from different agricultural sources in NRW; b) Net-exports of N for each county in NRW including manure exchanges with neighboring countries and states; c) Nitrate vulnerable zones in NRW at commune level

Source: Data for a) & b) retrieved from NRW nutrient report (LWK NRW 2014); Data for designated nitrate vulnerable zones from ELWAS-Web (LANUV 2020); Geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

3.3.2 Policy setup

The policy measures presented in this paper are derived from the revised FO 2017 and FO 2020. The selected measures were chosen based on the severity of their presumed impact on manure transports and their suitability to be modeled with an SPE model. A list of all measures of the FO 2017 can be found under (Kuhn 2017).

We evaluate the impact by comparing changes in N net-exports per ha (kg N ha^{-1}) compared to the baseline for both the bi-level calibrated and the uncalibrated model.

To allow for counterfactual analysis, the model is first calibrated based on the 170 kg N ha^{-1} application limit included in the FO 2007 (*baseline)*. In the counterfactual *biogasD*, N comprised in biogas digestate accounts additionally towards the 170 kg N ha^{-1} application threshold. For the FO 2020 scenario, communes marked as NPH, based on the §13 of the FO, have to reduce their manure N application limit by 20 and 40 kg N ha^{-1} (*nitrogenRed 1/2)*. This reflects the measure to reduce total N application limits by 20% in NPHs (BMEL 2020). A similar measure introduced in Denmark showed that both mineral and manure fertilizer application levels were affected (Petersen et al. 2010). As we cannot model total mineral N application, the impact of this potential measure is addressed by sensitivity analysis, considering the two different levels of reduced organic application limits.

The scenarios are introduced into equation (7) which is modified in the different scenarios as follows. For *biogasD* and *nitrogenRed1/2,* biogas digestate is now accounted for in the manure use s_c in each commune. In the *nitrogenRed* scenarios the $maxApplRate_c$ is reduced for communes marked as an NPH.

$$s_c \leq ha_c * maxApplRate_c \tag{8}$$

Estimated parameters from the baseline calibration enter the minimization of transaction costs to landscape level for the calibrated model; the uncalibrated version uses transaction costs of 1 Euro per kg and km. Both versions work with updated constraints (7) and (8) in simulations.

3.3.3 Calibration

Before the assessment of the results, we have to clarify some model assumptions and how they jointly, with given data, impact the identification of flows and manure use in the model. For import into and export out of NRW, the NRW wide totals are fixed. Both the calibrated and uncalibrated model will have to find communes into which these quantities will be imported or from where they will be exported. Similar, for each commune, available manure is fixed. As a result, a given total amount of organic N (excreted N + import into NRW – exports out of NRW) available at landscape level must be distributed, either by applying it in the same administrative unit or by transporting it. To stabilize the model further, we force each commune to use at least 50% of the estimated manure application according to the regression described in Section 3.2.1.

Further, the uncalibrated model with the uniform transport price can be understood as a model which uses a next-neighbor approach to minimize total transport distances. That means for the export out of NRW, for example, that with total imports into NRW exceeding total exports, the algorithm will first allocate exports into the communes nearest the border and net it off with imports of the same magnitude. This becomes visible from the results in Table 3.1, where only one export flow of the 21 observed ones is identified correctly, with a MAPE[7] of 102%, and an additional one wrongly introduced, which captures the 55% remaining exports.

In contrast, the calibration step has two main means to improve over the next-neighbor approach of the uncalibrated model. First, it can estimate a manure use price for each commune. By, for instance, reducing the use price (= willingness to pay for manure) relative to other communes, it can trigger exports from this commune or prevent imports into it, even if the legal manure application limit is not reached. Second, it can adjust the per unit transaction cost as a function of distance, where parameters differ for the three types of flows captured by the model, i.e. inter-county transports, imports into and export from NRW.

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[7] We calculate the MAPE solely based on correctly identified flows, i.e. where both data and model results show a non-zero transaction.

Table 3.1: Results for exports out of NRW with the calibrated and uncalibrated model in the baseline

				Transports grouped in size classes [tons N]				
		Unit		All	<1	1-10	10-100	100-1000
Quantity	Observed N quantity	tons of N		2079	2	33	210	1834
	Simulated N quantity	tons of N	calibrated	2079	-	-	-	2079
			uncalibrated	942	-	-	-	942
	Share simulated quantity	%	calibrated	100	-	-	-	113
			uncalibrated	45	-	-	-	51
	MAPE[1)]	%	calibrated	86	-	-	-	86
			uncalibrated	102	-	-	-	102
Frequency	Observed flows	frequency		21	3	6	8	4
	Simulated flows	frequency	calibrated	3	0	0	0	3
			uncalibrated	1	-	-	-	1
	Share simulated flows	[%]	calibrated	14	0	0	0	75
			uncalibrated	5	-	-	-	25

Table 3.2: Results for imports into NRW with the calibrated and uncalibrated model in the baseline

				Transports grouped in size classes [tons N]					
		Unit		All	<1	1-10	10-100	100-1000	> 1000
Quantity	Observed N quantity	tons		12416	1	4	224	3758	8429
	Simulated N quantity	tons	calibrated	12415		4	129	3841	8441
			uncalibrated	12015	-	-	68	3408	8539
	Share simulated quantity	%	calibrated	100	0	101	58	102	100
			uncalibrated	97	-	-	31	91	101
	MAPE[1)]	%	calibrated	22	-	1	20	17	34
			uncalibrated	64	-	-	0	93	44
Frequency	Observed flows	frequency		28	2	1	8	45	67
	Simulated flows	frequency	calibrated	20	-	1	3	10	6
			uncalibrated	10	-	-	1	5	4
	Share simulated flows	[%]	calibrated	71	-	100	38	91	100
			uncalibrated	36	-	-	13		

Table 3.1 further shows the improved fit for export flows with the calibrated model: it identifies 3 out of 4 larger exporting counties, compared to just one case for the uncalibrated one. All exports are also allocated in the correct size class, and no non-observed export is introduced. However, failing to introduce the smaller exports flows for some counties implies that the simulated flows in the size class 100-1000 are in sum 13% too large as total exports are fixed at landscape level.

In the uncalibrated model, additional imports exceeding re-exports will flow first into the commune nearest to the border, where the 170 kg limit is not exceeded, until this limit is reached. Remaining imports will then be disposed in the commune which is second closest to the border where the limit is not reached and so on. This led the uncalibrated model to identify 10 out of the 28 or 36% of the reported import flows (see Table 3.2). The resulting error is high with a MAPE of 64%. About 3% of imports are allocated to counties where no imports are reported. Imports into NRW are far better depicted in the calibrated model (see Table 3.2). The MAPE improves from 64% in the uncalibrated case compared to 19 % in the calibrated one. There are 68% of the observed flows correctly identified compared to just 36% in the uncalibrated one.

The uncalibrated model introduces transports to the nearest county with N absorption capacity for communes where the 170 kg limit is exceeded after accounting for imports into and exports from NRW. As inter-county trade can only be triggered by reaching the application limit under minimizing transport distances, the uncalibrated model only simulates about 18% of the observed inter-county trade quantities and identifies solely 2% of the observed flows (see Table 3.3). All seven identified flows fall in the largest size class which leads to a MAPE of 50% of the uncalibrated model.

Table 3.3: Results for inter-county transport flows in NRW with the calibrated and uncalibrated model in the baseline

				Transports grouped in size classes [tons N]				
		Unit		All	<1	1-10	10-100	100-1000
Quantity	Observed N quantity	tons		12050	38	142	6106	5329
	Simulated N quantity	tons	calibrated	5617	-	136	2296	3182
			uncalibrated	2150	0	0	0	2150
	Share simulated quantity	%	calibrated	47	-	-	38	60
			uncalibrated	18	-	-	-	40
	MAPE[1)]	%	calibrated	9	-	11	6	20
			uncalibrated	50	-	-	-	50
Frequency	Observed flows	frequency		356	38	142	153	23
	Simulated flows	frequency	calibrated	93	0	24	50	15
			uncalibrated	7	-	-	-	7
	Share simulated flows	[%]	calibrated	26	0	17	33	65
			uncalibrated	2	-	-	-	30

Table 3.4: Results for manure use in NRW with the calibrated and uncalibrated model in the baseline

				Manure use grouped in size classes [tons N]			
		Unit		All	10-100	100-1000	> 1000
Quantity	Observed N quantity	tons		170077	296	6116	163664
	Simulated N quantity	tons	calibrated	170077	251	5602	164224
			uncalibrated	170077	231	5255	164591
	Share simulated quantity	%	calibrated	100	85	92	100
			calibrated	100	78	86	101
	MAPE[1)]	%	uncalibrated	10	17	16	5
			calibrated	16	22	23	12
			uncalibrated				

The model fit of both model types is shown in Figure 3.3, by plotting observed transports against simulated (uncalibrated model) and estimated (calibrated model) transports. The diagonal line of the calibrated model results highlights the improved model fit (MAPE 9%) compared to the uncalibrated one (MAPE 50%). However, the effect of aggregation bias on inter-county flows remains clearly visible. While the calibration increases the number of identified flows by factor ten compared to the uncalibrated ones, only around one fourth of the reported flows are depicted. But whereas the uncalibrated model introduced just seven flows in total, all in the largest size class, the estimator also introduced quite small flows in the 1-10-ton category. Ten tons are equivalent to roughly 60 hectares applied with manure up to application limit, which underline the challenge for the estimator to depict such relatively modestly sized flows correctly. Compared to just 18% inter-county traded manure quantity covered by the uncalibrated model, the calibration reaches 46%.

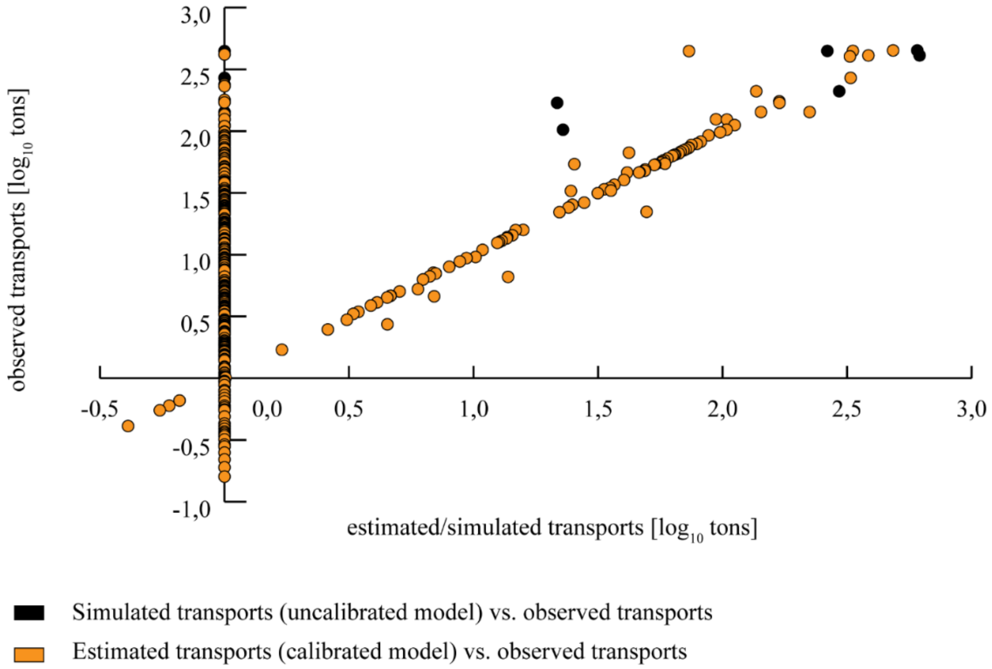

Figure 3.3: Simulated/estimated transports against observed transports [$\log_{10}$ tons]

Source:Own depiction

As the consequence of errors in depicted manure exchanges in the uncalibrated case, the amount of manure applied in each county as the main pressure indicator is estimated with a larger error of 16% in average, see Table 3.4. The improved estimation of manure exchanges implies a better fit for manure applied as well, see Table 3.4. While the MAPE drops from 16% to 10%, especially larger application quantities are far better depicted: 5% compared to 12% for the largest class, and 16% compared to 23% for the 100-1000 t class.

Using the information on imports and exports to determine net-transports, it becomes apparent that most counties are net-importing counties when out of state imports are considered (see Figure 3.4). The map indicates that larger net-imports in kg ha^{-1} both for the uncalibrated Figure 3.4a and calibrated model Figure 3.4b are observed close to the Dutch border. Further, it highlights that the major exporting counties are located in the north-west of the state which is in line with the major livestock producing regions. Comparing both models to the observed transports (Figure 3.4c), the results indicate that the estimated transport flows in the calibrated model are distributed similar over the entire study area compared to observed transports. The data from Figure 3.4 serves as the baseline to evaluate the impact of the calibration on the upcoming fertilizer policy scenarios.

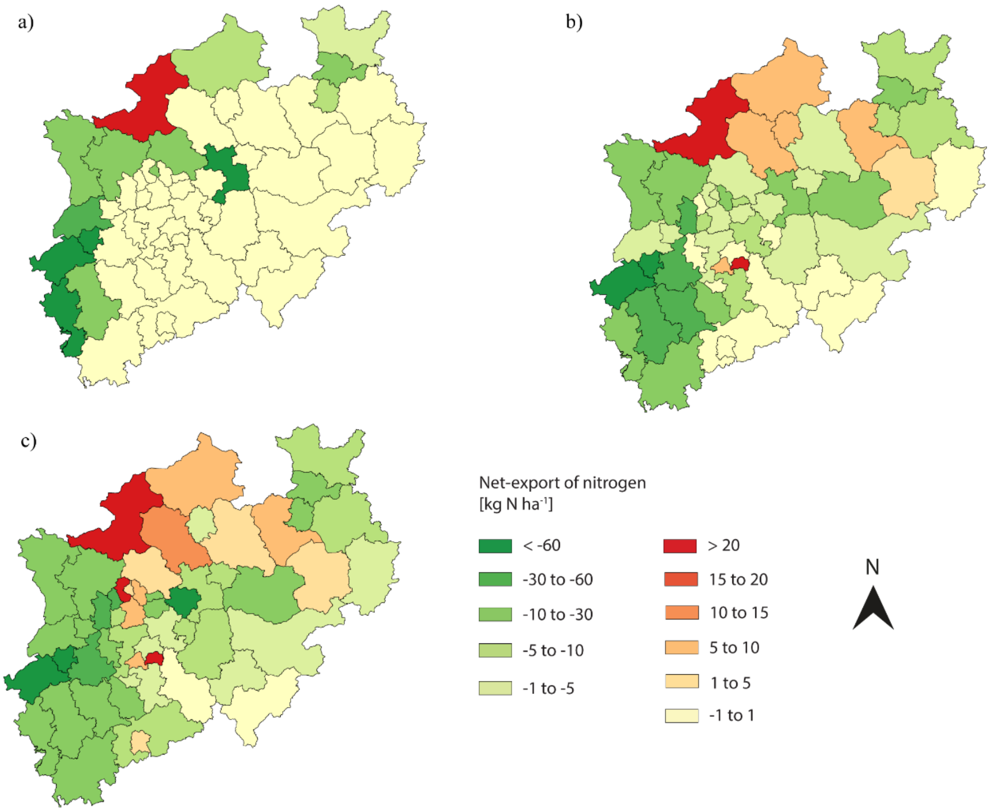

Figure 3.4: Net-export of N [kg N ha^{-1}] of the a) uncalibrated model, b) calibrated model, and c) calculated based on observed transports (LWK NRW 2014)

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

3.4 Results

3.4.1 Simulation results

The simulation results for manure transports in the study state NRW for the counterfactuals *biogasD* and *nitrogenRed1/2* are presented in N net-exports per ha for each county (kg N ha^{-1}). As in the above Figure 3.4, net-exporting counties show a positive sign and net-importing counties a negative one.

Figure 3.5 illustrates the *biogasD* scenario results for net-exports with the uncalibrated (Figure 3.5a) and the calibrated model (Figure 3.5b). Results of the uncalibrated model indicate a larger impact of this policy measure in the two most livestock intensive counties and their immediate neighbors. Further, this policy change triggers a shift in import destinations from out of state towards the southwest corner of NRW, as other border counties reach their N application limit at county level. In the calibrated model, the level of net-exports of N for the largest exporter is lower, with 19 kg N ha^{-1} compared to 27 kg N ha^{-1} in the uncalibrated model. Nevertheless, a larger number of the livestock intensive counties are increasing their manure exports to adjacent counties and to urban areas (Figure 3.5b). Further, the calibrated model suggests that predominantly counties in the arable farming region of the southwest are shifting imports, with some counties increasing their imports from livestock intensive counties and some decreasing their imports which is implied by the positive net-exporting values.

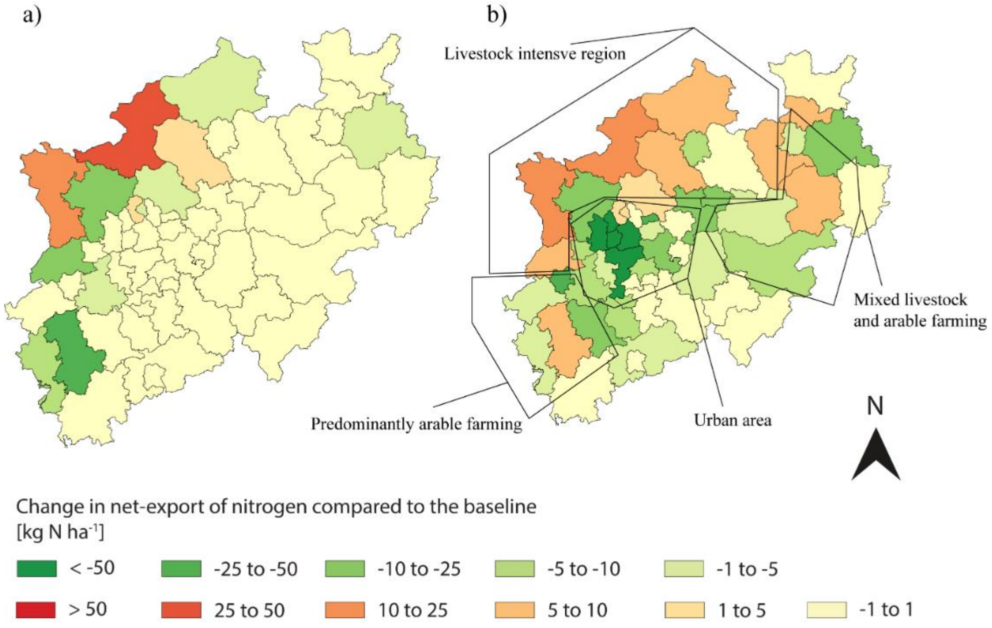

Figure 3.5: Change in net-exports of N [kg N ha^{-1}] for all counties in the federal state of NRW compared to baseline for the *biogasD* scenario, a) uncalibrated and b) calibrated model.

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

The results for *nitrogenRed1* show a similar pattern where in the uncalibrated model (see Figure 3.6a) net-importing counties are primarily located adjacent to the exporting counties and in the calibrated model (see Figure 3.6b) other counties further away from the exporting ones are starting to increase their imports as well. In addition, the calibrated model reports 12 counties increasing net-exports compared to only seven counties in the uncalibrated model. The level of net-exports increases in the most affected counties by up to 49.6 kg N ha^{-1} in the uncalibrated and 38 kg N ha^{-1} in the calibrated model. However, in both models, high level of N imports can be seen in the urban districts and the arable farm area, now absorbing manure imports from the Netherlands.

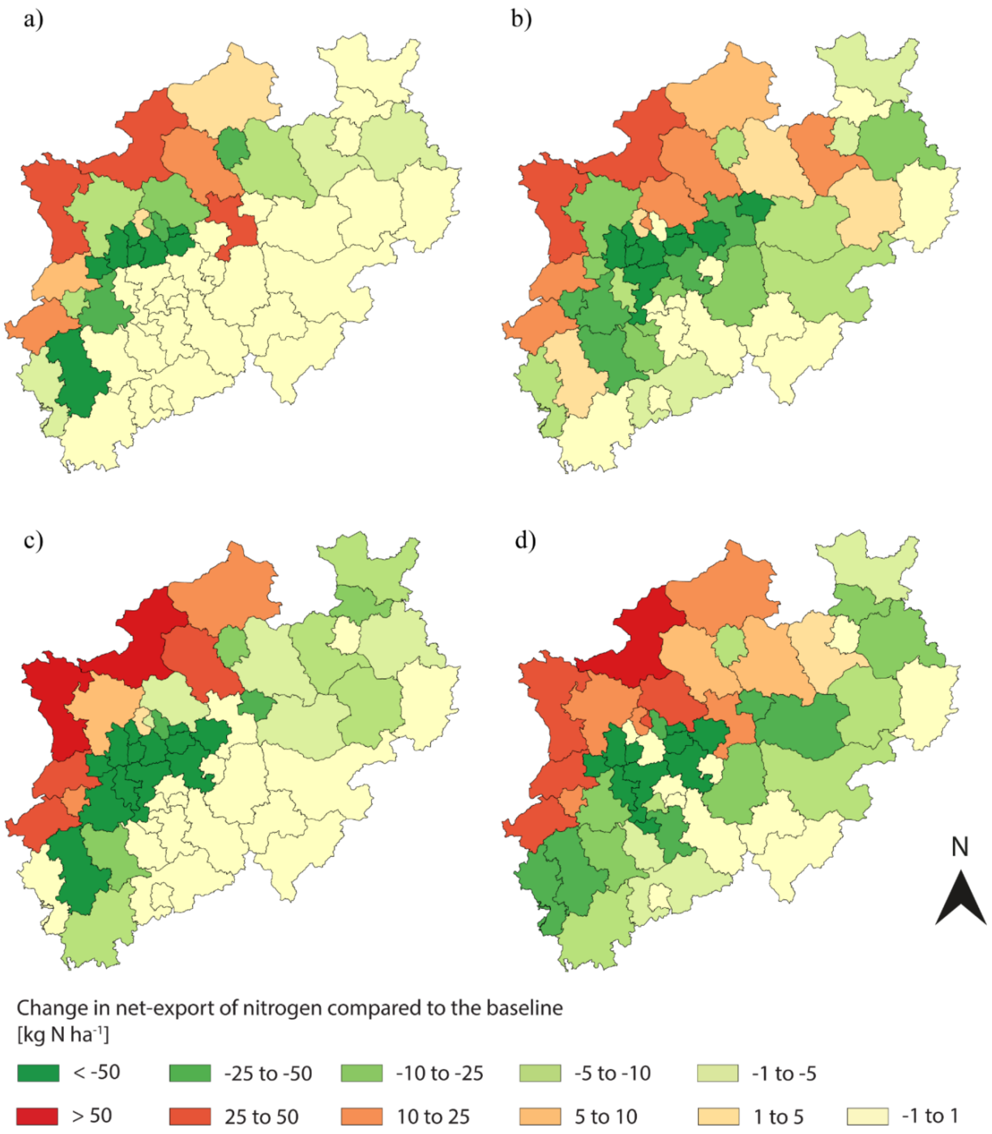

Figure 3.6: Change in net-exports of N [kg N ha^{-1}] for all counties in the federal state of NRW for a) uncalibrated model in *nitrogenRed1* b) calibrated model in *nitrogenRed1* c) uncalibrated model in *nitrogenRed2* d) calibrated model in *nitrogenRed2*

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

Figure 3.6d) highlights that almost every county in NRW is affected in the calibrated model under a reduced application limit of 130 kg organic N ha^{-1} in communes with a large share of NPH. This condition is true for the entire livestock intensive region where counties increase their net-exports between 10 to 56 kg N ha^{-1}. This causes larger counties dominated by arable farms to increase net-imports up to 53 kg N ha^{1}. Most of the adjacent urban districts import up to their application limits in the calibrated model, similar to the uncalibrated model as seen Figure 3.6c). These transports contribute, however, little to reduce the overall pressure due to small agricultural land coverage in these counties. The results for the uncalibrated model indicate that still parts of the study area are not participating in the manure trade and those participating are exporting or importing more compared to the calibrated model, respectively.

Table 3.5: Total aggregated county exports (as a proxy for transports) of N and change in transports compared to baseline

Scenario	Units	Calibrated	Uncalibrated
Baseline	total [tons]	5616	2595
biogasD	total [tons]	8039	4937
	Relative to baseline [%]	43.14	90.18
nitrogenRed1	total [tons]	12076	9773
	Relative to baseline [%]	115.02	276.49
nitrogenRed2	total [tons]	19010	19425
	Relative to baseline [%]	238.49	648.32

The results in Table 3.5 show that the calibrated model transports more than twice as much N in the baseline compared to the uncalibrated one. This outcome reflects that transports in the uncalibrated model are only simulated if application limits at commune level are exceeded. The calibrated model simulates more inter-communal trade to fit observed transport flows. In the counterfactuals, the uncalibrated model reacts more strongly in relative terms. In the scenario *nitrogenRed2*, the difference in total exported manure between uncalibrated and calibrated amounts to 415 tons. This stark increase in the uncalibrated model can be attributed to the fact that it allocates out of state imports as close to the border as possible to reduce transport costs by filling them up to their absorption capacity. Any additional N accounted for or not allowed to be applied any longer must hence be exported. In contrast, in the calibrated model imports from out of state are already transported further state inwards which dampens to some degree the need of border counties to export N in the counterfactuals.

3.5 Discussion

3.5.1 Bi-level calibration in the SPE manure market model

The application of the SPE model in combination with a bi-level calibration shows several advantages compared to using an uncalibrated model when analyzing manure transports. The estimation considers unobserved transaction costs which cannot be explained by the (usually constructed) transport distances between the administrative units. That leads to a sizeable improvement in depicting observed manure transport flows, both in terms of transport quantities and depicting transports where they occur. The uncalibrated SPE model generates similar results as the next-neighbour approach for manure by Auburger et al. (2015) and resembles the simulated decision behavior on the manure market in the studies by van der Straeten et al. (2011) and Willeghems et al. (2016), where transport decision behavior is steered solely by the imposed fertilizer regulations. The bi-level calibration improves upon these approaches by taking implicitly other transaction barriers than physical distance into account, such as odor nuisance, fluctuating nutrient content, or scheduling manure application (Case et al. 2017; Asai 2013). Further, the calibration approach also correctly depicts long-distance transports already in the baseline and consequently also captures interactions between more distanced regional units in the simulations.

Distances in the model reflect existing road infrastructure instead of the more usual bee-line approach as in Auburger et al. (2015). This can improve SPE models even without a calibration exercise. However, limitations of our SPE modeling approach to manure exports are relevant for both the calibrated and uncalibrated version. First, missing data prevent a differentiation between different manure types and their nutrient content, which in reality is likely to influence the behavior of farmers to reduce the use of mineral fertilizer in favor of manure. The model does not consider additional and alternative compliance options such as available manure treatment options which increase nutrient contents and decrease transport costs (Hou et al. 2016). Equally, willingness to pay for manure as depicted by the manure price remains unchanged between simulations but is likely to be affected by policy changes. For example, (more) farms with high livestock densities may start to pay importing farmers under stricter legislation to find partners willing to accept their manure.

Second, assuming cost minimizing behavior excludes counter-trade between communes, which are in reality frequently observed in NRW (LWK NRW 2014). This can be understood as aggregation bias from treating communes as aggregated agents. It reduces the number of reproduced transports between counties to a moderate level with the calibrated model in the baseline (Section 4.1). In contrast, the uncalibrated captures very few of the observed inter-county trade connections as uniform per unit transport costs would suggest filling up first each unit up to their maximal application limits.

The computationally demanding calibration exercise asks for a compromise between spatial coverage and agent detail, respectively. Disaggregating to farm types by commune, for instance, is impossible for the whole of NRW, but could be considered for smaller case studies. A SPE model operating at a smaller landscape could optimize additional mitigation options, such as manure treatment, substituting mineral fertilizer against manure application, adjusting crop yields and choice, or reducing livestock densities. This might allow to address further measures of the FO such as P_2O_5 surplus restrictions which might trigger additional manure exports, especially for pig farms (Kuhn et al. 2019a).

Farmers in NPHs have to reduce their overall N application by 20% under the revised FO’20. Based on empirical data from Denmark (Petersen et al. 2010) and NRW (LWK NRW 2018b), we assume that the reduction affects solely manure application. Therefore, results for *nitrogenRed1/2* rather hint at trends in changing transport patterns.

3.5.2 Calibration impact on the analysis of the fertilizer regulations

Simulation results differ distinctly between the calibrated and uncalibrated model, both with regard to the regional distribution pattern and the quantity of transported N. With equal transport costs per unit in each county, the uncalibrated model minimizes overall transport distances. This leads to a high concentration of N in the livestock intensive counties, in the counties bordering the Netherlands, and their adjacent ones. Especially the policy shift in *nitrogenRed1/2* which triggers considerable additional nutrient exports in both model versions highlights that the uncalibrated model favors short-range transports and consequently concentrates the additional exported manure quantities in a few counties compared to the calibrated model.

The calibrated model reproduces a moderate level of N flows in the baseline, which not only leads to transports from exporters to surrounding counties as in the uncalibrated model, but also to more distanced counties. This implies a wider distribution of N in the *biogasD* and *nitrogenRed1/2* scenarios. However, as in the uncalibrated model, direct neighbors of livestock intensive counties and border counties remain the primary importers. In comparison to the uncalibrated model, the results of the calibrated model seem more plausible as existing manure application infrastructure can be used in counties which are already importing in the baseline, including more distanced ones. The calibrated model seems therefore more suitable in the analysis of fertilizer policy impacts as it depicts also long-distance transports, which are to some extent already observed in the baseline.

3.5.3 Policy considerations

At least two policies indicate that policymakers in NRW favor (increased) manure exchanges over relocation of livestock farming or overall reduction of livestock numbers. First, financial contributions support the so-called nutrient exchange (“Nährstoffbörse”), which comprises nutrient brokers, state-run agricultural advisory work stations and laboratories which test nutrient contents in manure (Nährstoffbörse 2019). Second, the manure shipment ordinance (“Verbringungsverordnung”, WDüngV) prescribes to monitor manure nutrient contents to provide more reliable information to importing farmers. Both policies reduce transaction costs of manure trading and are thus likely to increase traded quantities.

However, major barriers for manure transports remain, especially into regions with a high share of arable farms and a small number of NPH marked communes, as seen in the *nitrogenRed1/2* scenarios with the calibrated model. Previously importing counties reduce imports significantly or even shift to exports, whereas regions with arable farms and non-polluted water bodies increase imports. In these counties, new investments are necessary. Required timely manure applications are unlikely realized with massive manure transports between counties in rather short time frames, which asks for additional intermediate storage facilities. Equally, existing machinery parks necessary for manure applications needs to be extended, as moving equipment in a just-in-time fashion over wider distances is unlikely. Especially, during periods where all farmers at landscape level favor manure applications, due to vegetation stages, soil and weather conditions.

Odor nuisance is found in many studies as a major hindrance to let farmers accept manure (Núñez und McCann 2004; Case et al. 2017), based on concerns about their ‘standing’ in the community (Asai et al. 2014), especially in areas with few livestock or in more urban districts. Odor nuisance and resistance against additional traffic of lorries and agricultural machinery can trigger initiatives against new manure storages, rendering permission procedure more costly or even preventing investments. Policymakers have multiple options to address these issues. First, investment subsidies can increase acceptance rates of farmers (Case et al. 2017). Second, simplified and streamlined procedures regulating the construction of manure storage facilities can speed up investments and lower their costs. Third, subsidies can support odor reducing technologies, such as acidification of manure (Sommer et al. 2017), or promote the transport and application of biogas digestate with a lower odor burden (Hansen et al. 2006; Hjorth et al. 2009). Informational campaigns on the benefits of manure as a source of nutrients and organic matter in arable farming systems can also help to reduce resentments.

Policymakers might favor even long-distance manure exchanges as they not only reduce nutrient surpluses and compliance costs on farms with high livestock densities but might also improve soil structure and reduce fertilizer costs by substituting inorganic fertilizer with inexpensive manure in importing farms. However, manure exchanges can provoke pollution swapping, i.e., a shift between different pollutants (Stevens und Quinton 2009) or different regions (Oenema und Velthof 2007). Increasing manure transports over long distances likely increases GHG emissions in the manure application chain (Kuhn et al. 2018). Even more critical is increased NO_3^- leaching in importing farms as found by (Kuhn et al. 2019b). The considerable imports of manure into so-far hardly polluted regions simulated under the new FO suggest, for instance, to monitor and to control closely the nutrient status in these regions, and to raise awareness of potential risks of manure applications by extension services with importing farmers.

3.6 Conclusion

This study develops a bi-level based calibration approach for a SPE manure transport model at landscape level, applied to assess impacts of selected measures of the revised FO. The key policy measures examined in this study are the accounting for plant-based biogas digestates in the maximal application rate of 170 kg N ha^{-1} (*biogasD),* and a stepwise reduction of the N application limit from 170 to 130 kg N ha^{-1} in NPHs (*nitrogenRed1/2)*. Both measures are simulated with a calibrated and uncalibrated model version, and their results compared. The federal state of NRW in Germany serves as the case study region, characterized by regions with high livestock densities and biogas plant numbers as (potential) manure exporters, adjacent to regions dominated by arable farms as (potential) importers.

The study shows that bi-level optimization can improve the parameterization of resource allocation problems where optimizing behavior is assumed. The calibrated model recovers 47% of the observed transport quantity and 26% of the observed transport links, compared to 18% and 2%, only, in the uncalibrated one. The calibrated version depicts better observed manure application rates and captures observed long-distance transports not simulated by the uncalibrated version.

However, computational restrictions still limit model size and policy detail in bi-level applications and SPEs. Moreover, not all observed behavior might be explained by optimizing rational. Our model covers 396 communes and considers manure trade up to distances of 120 km. Model size and missing data prevents the consideration of other compliance strategies besides manure exports or disaggregating the communes further, for instance, to different farm types. The latter implies the exclusion of two-way trade between communes.

Results for *biogasD and nitrogenRed1/2* highlight the importance of accounting for long-distance transports. The simulated necessary expansion of manure imports to comply with the new FO is likely to meet considerable obstacles especially in communes where so far no or limited amounts of manure are applied. Policies might be asked to support expanding manure storage and application infrastructure, to streamline permission procedures of manure storage facilities, and to tackle resentment towards manure due to odor nuisance. At the same time, the need arises to carefully monitor potential pollution swapping provoked by increased manure imports.

3.7 References

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Chapter 4

Modeling policy induced manure transports at large scale using an agent-based simulation model[8]

Abstract

ABMSim an agent-based model (ABM), is extended and applied to model short- and long-distance manure transports induced by the revised German Fertilization Ordinance (FO). It quantifies impacts on manure transports (max. 150 km), regional nutrient balances, and farm types, covering the farm population (~34,000 farms) of North Rhine-Westphalia (NRW), Germany (~35,000 km^2). The large study area is realized by using an estimated meta-model based on simulation results with the detailed bio-economic farm model FarmDyn. Results indicate that manure exports increase due to FO measures related to phosphate (P_2O_5) surpluses in pig farms, whereas increased transport distance is found in dairy and pig farms due to competition in the manure market. The study underlines that ABM applications for larger populations and landscapes are possible by reducing the computational load through meta-models. Future research can address improved meta-models based on econometric estimation or machine learning as well as feedback between manure market and its participants.

Keywords: Agent-based model, environmental regulations, manure transport, Nitrates Directive

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4.1 Introduction

In the European Union, the Nitrates Directive (ND) and the Water Framework Directive (WFD) are the primary policies to prevent nitrogen (N) and P_2O_5 losses from agricultural sources to the environment (European Council 1991). The national implementation of the ND and WFD governing fertilizer use in the agricultural sector causes many livestock regions in the European Union to rely on manure exports to prevent disruptive structural changes (Willems et al. 2016; van Grinsven et al. 2016). The German government revised the FO as the implementation of the ND in 2017 after infringement proceedings by EU Commission. The EU Commission judged this revision still insufficient to meet the target of the ND in German ground and surface water bodies. The German government has therefore decided to have further amendments to be implemented from 2020 onwards (BMEL 2020).

In literature, various adaptation strategies of farmers to comply with the mandatory measures of the national implementations of the ND have been analyzed at farm (Kuhn et al. 2019; Belhouchette et al. 2011) and regional level (van der Straeten et al. 2011). Single farm modeling can depict policy measures and simulate related compliance responses in great detail while accounting for farm heterogeneity (Mack und Huber 2017). The study by Kuhn et al. (2019), for instance, minimized compliance costs for a representative farm sample related to the 2017 amendment of the FO in a highly detailed bio-economic programming model and found manure exports as the primary adaptation strategy. As each farm is independently solved, such analysis cannot depict consistently that higher manure exports in some farms require (increased) imports by others and quantify the related pollution swapping. Moreover, how much manure each farm exports depends on transport and transaction costs which are exogenous in farm modeling but are likely changing when manure trade increases at landscape level.

This motivates the application of regional manure market models, such as the SPE models by van der Straeten et al. (2011) and Willeghems et al. (2016). They explicitly simulate manure transports between spatial units, accounting for transport distance and related costs, to identify exporting and importing districts and the related regional distribution of nutrients. Due to computational restrictions, existing models of this type depict administrative units such as communes as importing and exporting agents. Differences in nutrient levels across farms inside each unit are averaged out and policy measures can be simulated only for an artificial average farm. This limits their ability to quantify impacts from policy changes in detail.

This study addresses these limitations by combining the farm-level and regional market approaches in an ABM. Agent-based models allow to integrate the strength of detailed single farm level models and simultaneously depicts their interactions at landscape scale (Happe et al. 2011; Troost und Berger 2015). This offers two key advantages when analysing manure transports. First, the underlying "bottom-up" approach explicitly represents farm heterogeneity in space by depicting each farm as an independent decision taker, avoiding aggregation bias (Huber et al. 2018). Second, SPE models have to assume transport costs minimization in perfect markets, whereas ABMs can depict interactions governed by other institutions and different behaviour (Huber et al. 2018), to better capture the real-world environment.

Modeling manure flows with an ABM face two major challenges. First, an ABM should be able to cover a large area with thousands of farms to reflect that sizeable manure transports between administrative units which are 50 km or more apart are frequently observed (LWK NRW 2018). ABMs, which depict decision behavior based on mathematical programming models specified for each single farm (Happe et al. 2011; Troost und Berger 2015) covered so far only smaller regions of maximal 1700 km^2 (Huber et al. 2018) due to computational restrictions. The alternative approach to work with far simpler models (Zimmermann et al. 2015; van der Straeten et al. 2010) might not be able to depict policy measures and related abatement strategies in detail. Second, to generate a farm population in an ABM representing the true one is often difficult due to data scarcity and data protection and often requires own survey work (Valbuena et al. 2010), or the generation of an artificial farm population where, for instance, the spatial distribution of farms by types or other characteristics is taken from a non-representative farm sample (Zimmermann et al. 2015).

The research contribution of this paper is threefold. First, we develop a method to generate a heterogeneous farm population at landscape scale by combining data from the FSS and other statistical data using a highest posterior density (HPD) estimator (Heckelei et al. 2008). This captures the spatial distribution of important farm characteristics at commune level while complying with data protection laws. In the case study state of NRW this encompasses a population of ~34.000 farms for all 396 communes. Second, we overcome computational limitations based on a meta-modeling approach which replaces the programming models for each farm used in other agricultural ABM (Lengers et al. 2014; Seidel und Britz 2019). We estimate manure export functions from a large scale result set of the single farm level model FarmDyn (Britz et al. 2019). They are subsequently integrated in the agent-based Model ABMSim (Britz 2013) to depict the decision behavior of manure exporting farms in manure markets. Third, we apply the resulting ABM to simulate manure transports before and after recent changes in the FO 2017 on state level. The resulting insights into the impacts of measures of the German ND implementation on manure transports are of interest for an international readership as similar measures and considerable manure exchanges are found in many other European countries.

4.2 Methods

We apply the agent-based model ABMSim to analyze the impacts of the revised FO on manure transports and N distribution in NRW. This chapter presents the relevant features of ABMSim for the manure market (Section 4.2.1), the underlying farm typology (Section 4.2.2), followed by the key steps in the initialization and the location of farmsteads in space (Section 4.2.3). Further, it introduces important features in the context of manure transports such as the meta-modeling approach with FarmDyn to generate the decision behavior of manure exporters (Section 4.2.4). Eventually, we describe the theoretical framework of the manure market in ABMSim and the policy implementation (Section 4.2.5).

4.2.1 Agent-based model ABMSim

ABMSim is an ABM with a focus on the agricultural land and manure market, which can be used jointly or independently. Interactions between farms agents in land markets depict farm structural change, while manure markets link decisions of manure exporting and importing farms. Interactions are steered by an auction mechanism, by default a Vickery one. A detailed documentation of ABMSim can be found under (Britz 2013). This study simulates the revision of the FO in ABMSim in a comparative-static setting, neglecting structural change driven by farm exits or land exchanges.

4.2.2 Farm typology of the case study region NRW

Key in the development of the farm typology is the detailed representation of characteristics which determine manure imports, exports and related costs for the individual farm. We take farm specialization, farm size and livestock density as the main attributes which define both the legally allowed nutrient absorption capacity and the resulting nutrient export pressure (Kuhn et al. 2019). As spatial aspects (e.g., transport distances, regional concentration of farm types) are pivotal in the manure market, we aim to generate farm populations for each commune to provide heterogeneity at the smallest administrative level available from the FSS database. The FSS includes almost all farms in NRW, providing information on land use, farm size, livestock numbers and its communal affiliation. Further, it covers relevant information for the manure market such as manure storage capacities and manure application capacities. The FSS is subject to strict data protection laws which prevent access to single farm records. Even aggregated data at administrative levels such as communes and counties do not cover more complex cross-tables and comprise wiped out cells to avoid that data on single farms become visible or can be re-constructed. The available data for NRW and the heterogenous farm structure with both highly livestock intensive regions and regions dominated by arable farms make it an interesting region to assess the impact of the FO on the manure market.

The farm typology in ABMSim is based on the highest tier of the classification of single farms by economic specialization of the European commission (European Commission 2008). Further aggregations of farm types are made to reflect the farm branches available in the single farm level model FarmDyn. The resulting farm typology comprises arable, dairy, and pig fattening farms which are active on the manure market as well as a fixed farm type assumed to neither import nor export manure. The fixed farm type comprises farms such as permanent-culture, horticulture, or livestock farms with non-relevant animal counts in the region such as sheep and goats. Furthermore, farms are differentiated by size class in hectares in accordance with classifications available in the FSS (IT NRW 2018). Table 4.1 shows a complete list with all farm specific characteristics relevant for the manure market and the corresponding sources.

Table 4.1: Overview of relevant characteristics on the manure market for individual farms

Characteristics	*Description*
Location	Spatially explicit with affiliation to commune and county
Farm type	Arable, dairy, pig fattening, fixed
Size class	<5, 5-10, 10-20, 20-50, 50-100, 100-200, >200 [ha]
Land use	Acreage of arable, grassland and permanent cultures [ha]
Livestock units/density	Number of livestock units of all animals [LU] and livestock density [LU per ha]
Manure storage capacity	Manure storage capacity is given capacity related to the excretion of the herd in temporal terms [months]
Phosphorus soil status	The phosphorous soil status is given with values between 0 and 1. [1 – highest P content, 0 – lowest P content]
Biogas digestate	Plant-based biogas digestate as N on farm [kg]
Manure export estimation function	Manure export estimation function is only valid for farms with livestock

4.2.3 Initialization of the farm population and their spatial distribution

The initialization in ABMSim distributes farms based on farm type, size class, communal affiliation, and livestock density in space following four steps. First, we construct the heterogenous farm structure of NRW in the form of contingency tables with frequencies of farm types and size classes for each commune. Due to data security regulations of the FSS, data availability is limited on communal level. Thus, we use data on county and district level and available communal data such as number of farms per farm type and number of farms per size class. The available data is then used in a highest-posterior density estimator (Heckelei et al. 2008) to generate the communal contingency tables.

Second, the contingency tables on communal level are used to replicate the farm structure in space. To represent the land use and to distribute the farms in NRW, ABMSim uses the CORINE (‘coordination of information on the environment) land cover (CLC) database to construct the land use pattern for the year of 2012 (European Environment Agency 2012). With a geographically explicit landscape of one ha, information on different land uses including agricultural used area is given. Farms are located on agricultural land and each farm is assigned a certain amount of arable and grassland depending on their size class and farm type, where grassland is only distributed to dairy farms. Data on plant-based N from biogas digestate and the location of biogas plants is only available on county level (Landwirtschaftskammer

NRW 2018; Karbach-Nölke 2017). Hence, we assume that biogas digestate is allocated according to a weighting factor to the communes. The weighting factor is determined by the amount of maize silage acreage within the communes, as maize silage is by far the most important primary input for biogas plants in NRW. With no information on which farms have a biogas plant, the biogas digestate allocated to a commune is then distributed equally on arable land to each farm within the commune.

Third, to allocate livestock to each pig fattening and dairy farm, respectively, we use data of livestock densities and numbers from the Thuenen-Atlas (Gocht und Röder 2014) and FSS. In accordance with the information of livestock densities, each farm is assigned randomly a livestock density within the given data range by the Thuenen-Atlas. The livestock density and total acreage of the farm determine the livestock units for each farm. These are afterwards scaled such that the reported total livestock units on communal level are met. To determine the total N excretion of a herd, we use the average N excretion per livestock unit of 10.000 farm simulations with FarmDyn for dairy and pig fattening farms, respectively. The data on excretion in FarmDyn is based on the excretion levels after storage losses given by the FO 2007 and FO 2017 (BMEL 2017, 2007).

Fourth, the remaining farm characteristics used in the meta-modeling approach to estimate manure exports such as the P soil status and manure storage capacities are distributed. The manure storage capacities are distributed using a Latin Hypercube sampling approach with a range taken from Osterburg und Techen (2012). The P soil status depends on the location in NRW and information on the P soil status of each region is also taken from Osterburg und Techen (2012).

4.2.4 Meta-Model for manure export estimation

The behavior of exporting farms on the manure market in ABMSim is determined by a manure export function. The manure export function estimates the likelihood of a farm to export manure and the exported amount based on a tobit-regression model (Figure 4.1). To estimate the manure export function, we adopt and extend a meta-modeling approach previously developed by Lengers et al. (2014) using the highly detailed bio-economic single farm model FarmDyn.

The meta-modeling approach follows a five-step procedure. First, observed distributions for all explanatory factors in the estimation are taken from the descriptive statistics of the farm population in NRW as described in the previous section. Second, a farm sample with 10,000 dairy and pig fattening farms, respectively, is generated by a Latin Hypercube sampling. The relevant explanatory factors for manure exports and their distribution in the population are taken from Kuhn et al. (2019), which estimates compliance costs to the FO. Further, we add price data on milk, pork, and manure export costs as explanatory factors. For a full list of the explanatory factors and its ranges please refer to Appendix 4.1.

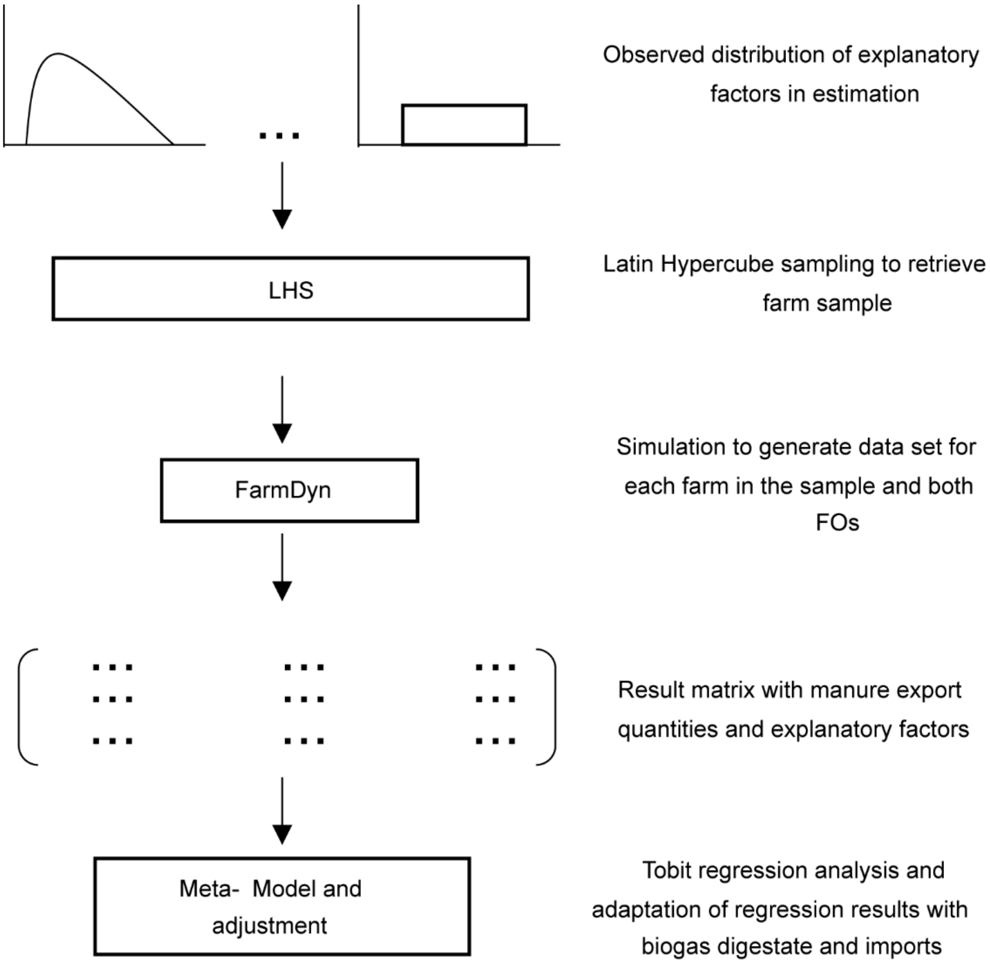

Figure 4.1: Meta-Modeling approach to estimate the manure export function

Source: Own depiction based on (Lengers et al. 2014)

Third, each farm is optimized with FarmDyn under the FO 2007 and the FO 2017, which generates the observations for the subsequent estimation of two meta models for pig and cattle farms. The optimization takes all relevant measures of the FO into account such as banning periods for manure application, different N and P_2O_5 application limits, and required manure storage. For a complete list and description of the FO 2017 changes see Kuhn (2017). Biogas digestate is not accounted for in the estimation of the meta model as we do not simulate farms with biogas plants. The simulated manure export quantities for each farm are part of a profit maximal compliance strategy which considers simultaneously alternative adjustments at farm scale such as reducing herds, adjusting crop acreages, and switching to N-reduced feeding. Thus, the observations implicitly comprise information how, for instance, higher manure transport costs impact the profit maximal compliance strategy.

Fourth, we retrieve the resulting matrix with manure export quantities and data for all explanatory factors to be used in the estimation step, and fifth, as we observe a larger share of non-exporting farms in the generated dataset, we opt for a tobit regression model with a left cut-off at zero for manure export volume as the dependent variable. To find a good fit for the meta-model we include for all chosen explanatory factors logarithmic, squared, square root, and interaction term effects. Multicollinearity is addressed by removing explanatory factors with a correlation higher than 0.99. This soft cut-off reflects that exact determination of the individual coefficients is not at the core of the estimation based on 10.000 observations. The high non-linearity of the meta-model could lead to implausible estimates outside the observation range. This is not a problem in here as the farm population in the ABM provides the basis to construct the observation samples. We run for each FO the tobit regression model on the farm sample of dairy and pig fattening farms, respectively, using the R-Package “AER” (Kleiber und Zeileis 2020).

The intercept of the tobit regression model of each farmer is increased by plant-based biogas digestate for the FO 2017. In the FO 2007, plant-based digestate was not accounted for in the N application limit. Values for plant-based biogas digestate are allocated to each farm in the initialization step. The meta-model results for each farm type and each FO are shown in Appendix 4.2.

4.2.5 Manure market in ABMSim

The manure market in ABMSim is based on an auction mechanism in which pig and dairy farms export manure and arable farms import it. In the auction, importing farms offer manure application contracts (MAC). They specify the location of a farmstead and the amount of manure barrels which the importing farmer is willing to accept. The size of each manure barrel is 21 m^3 as a standard size for manure transport barrels. We implemented fixed contracts sizes for manure barrels to import either 30, 20, 10, 5, 2 or 1 barrel(s), which are traded in the auction starting with the largest contracts. The number of contracts and their size of an importing farmer reflects its arable land endowment and the maximum allowed N application limit of 170 kg N ha^{-1} in the FO. Even if in other farm types, like pig farms for example, the farm P_2O_5-balance is binding in the application of organic fertilizer due to FO measures (Kuhn et al. 2019), we assume that the P_2O_5-supply soils in arable farms is mostly low and is therefore not considered in the nutrient uptake capacity.

Exporting farms bid on the MAC offered by importing farmers up to distance of 150 km. The distance between the exporting and importing farm determines the transport costs for the MACs. The export function determines based on the specific costs each MAC along with farm specific factors the profit maximal manure export quantity (see Section 4.2.4 and Appendix 4.2). A crucial aspect of the export function is that with increasing transport costs the amount of manure export quantity decreases, and the farm implicitly uses other on-farm compliance strategies such as N reduced feeding. However, as we do not have a feedback to the farm endowments, we do not know if such a compliance strategy is the reduction of livestock, which can result in farms exceeding the FO nutrient thresholds. All other explanatory variables of the function besides export costs for manure are fixed. As a result, as larger contracts are auctioned first, farms tend to grab bids for contracts in their immediate vicinity. Here, at lower transport costs, profit maximal export quantities are higher. The mechanism renders it also more likely that larger farms with higher export requirements get a tender in the auction contracts. This also entails, that farms might not be able to export their entire excess manure. This happen if no importing farms in their vicinity have ample nutrient absorption capacity and transport costs for long-distances reduce the amount of optimal export quantities.

The FO is implemented differently for livestock compared to arable farms in the manure market. For livestock farms, measures and restrictions imposed by the FO are reflected in the manure export function based on simulation results of FarmDyn which considers all relevant measures of the FO 2007 and FO 2017. As shown by the study of Kuhn et al. (2019) this relates mainly to a P_2O_5-balance restriction for pig farms and the N application limit of 170 kg N ha^{-1} for dairy farms. For arable farms, the maximum amount of imports depends on the 170 kg N ha^{-1} application limit and farm size, only, as we assume that arable farms are not operating on P_2O_5 enriched soils. Other adaptations of importing farmers or P_2O_5-balances are assumed to be not of relevance for arable farms which constitute the importing site of the manure market in ABMSim.

Offering MACs related to the largest number of barrels first in auction let importing and exporting farmer minimize their transaction costs. Further, we assume that in case where multiple exporting farmers offer a bid, the one with the shortest distance and thus lowest transport costs to the importing farmer gets the contract. This would allow the maximum pay-out to the importing farmer to accept the manure. This rule also reflects that manure transports are often organized by contractors which can be assumed to minimize their transport costs. Appendix 4.3 gives further detail on the auction mechanism.

4.3 Results

This study assesses the impact of the revised FO 2017 compared to the FO 2007 on manure transports and N at landscape level for the state of NRW in Germany. First, we have a critical look at the initialization of the farm population, specifically at the distribution of factors relevant for manure markets. Next, we compare simulated manure transports for the FO 2007 with available data on observed manure transports (LWK NRW 2018). The simulation for FO 2017 accounts also for plant-based biogas digestate and is based on an updated manure export function for each livestock farmer to the FO 2017.

4.3.1 Initialization and validation of the manure market

Table 4.2 shows that the initialization fits very well with regard to the number of farms by farm type for NRW as a whole. The HPD estimator generating the farm population needs to find integer values fitting estimated contingency tables for the 396 communes. This is computational quite demanding and provokes the reported slight differences. Equally, merging data on land use given by the FSS and CORINE reproduces well the hectares for relevant agricultural land uses. The farm types (i.e., dairy, pig and arable) participating on the manure market make up 79.8% of the total farmer population and add up to 77.6% of the total utilized agricultural area. We distribute all livestock from cattle and pigs to their respective farm types, the remaining livestock (poultry, horses, sheep, and goats) reported in the FSS take not part in the manure market. But their N excretion according to the FO as derived from the Thuenen-Atlas is considered when reporting N indicators for each commune. The chosen aggregation to arable, dairy, pig, and fixed farms in ABMSim is different from the FSS typology and therefore not compared to FSS data in Table 4.2.

Table 4.2: Initialization results for land-use, livestock, and number of farms for NRW

	Source	Unit	Total	Arable	Dairy	Pig	Fixed
Number of farms	ABMSim[a]	Count	33736	9288	12338	5314	6796
	FSS[b]		33688	9282	12369	5302	6735
UAA	ABMSim[a]	‘000[ha]	1394	400	476	206	310
	FSS[b]		1440	-	-	-	-
Arable land	ABMSim[a]	‘000[ha]	1086	400	168	206	310
	FSS[b]		1035	-	-	-	-
Grassland	ABMSim[a]	‘000[ha]	307	-	307	-	-
	FSS[b]		392	-	-	-	-
Livestock Units	ABMSim[a]	‘000[ha]	1543	-	895	648	-
	FSS[b]		1835	-	-	-	-

Remark: [a]ABMSim initialization results, [b] IT NRW (2018)

Figure 4.2 shows net-exports for each county as simulated for the FO 2007 with the baseline (a) and (b) the difference to the nutrient report. A positive sign implies a net-exporting county, whereas a negative sign indicates a net-importing county. Net-exporting counties are located in the northwest, net-importing counties in the east and southwest. Compared to the nutrient report data, simulated exports for net-exporting counties tend to be underestimated as indicated by the green color, up to -28 kg N per ha for the largest export. This also implies lower imports of net-importers such that we simulated somewhat lower manure trade in the baseline compared to observed data. We discuss potential reasons in Section 4.4.1.

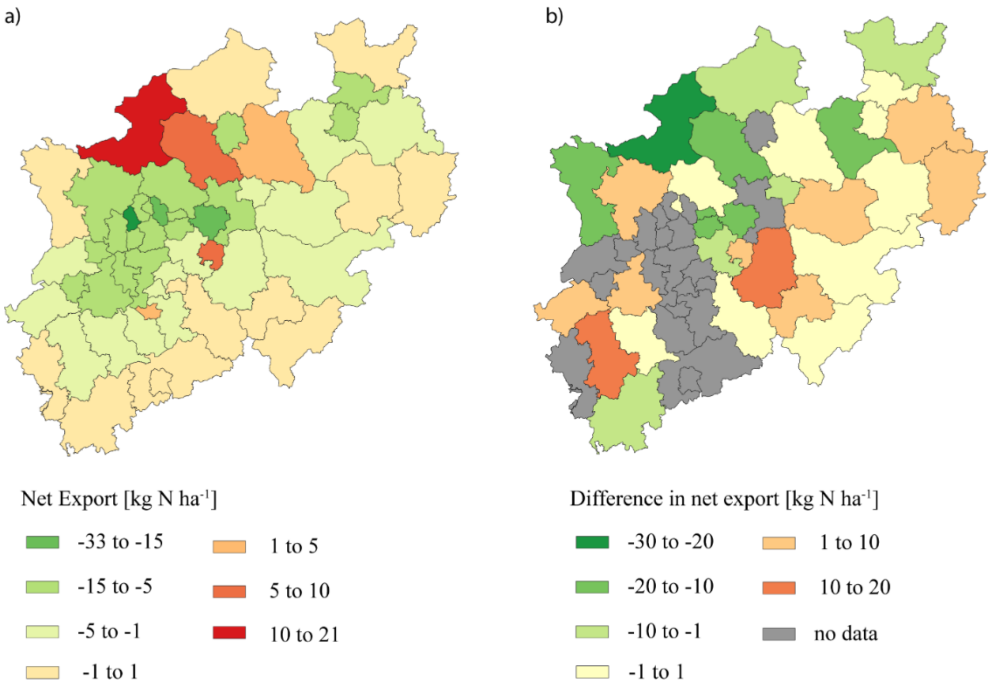

Figure 4.2: a) Net exports in the baseline under the FO 2007; b) Difference in net exports between FO 2007 and nutrient report 2016 (LWK NRW 2018)

Remark: There is no single data for counties indicated in grey.

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

4.3.2 Simulation results

Figure 4.3 shows simulated average remaining organic N per commune, aggregated from single farm level. It depicts organic N availability as the sum of manure excretion of all animals as reported in the Thuenen-Atlas plus plant-based biogas digestate for the FO 2017 minus simulated net-exports. Baseline results (Figure 4.3a) show regions with higher-than-average organic N excretion in the northwest and west of NRW, especially in communes close to the Dutch border. Values range from moderate 120 kg N ha^{-1} to 210 kg N ha^{-1} in communes with extremely high livestock densities. Moderate livestock densities and thus organic N levels are found in the southeast of NRW, ranging from 90 kg N ha^{-1} to 150 kg N ha^{-1}. There are two regions specializing in arable farming in the east and in the southwest with low average organic N levels on all farms with less than 35 kg N ha^{-1} at communal level even after accounting for manure imports.

The measures of the FO 2017 show an effect especially in the region with high livestock densities and in the lower-than-average communes in the east and southwest. Some communes in these net-importing regions increase their average organic N levels up to 140 kg N ha^{-1}. This reflects both the accounting of plant-based biogas digestate under the FO 2017 and higher imports in these regions dominated by arable farming.

In the previously high average N region, the results show a decrease in organic N levels of -10 up to -40 kg N ha^{-1} in almost all communes, despite the fact that biogas digestates are now accounted for. This reflects more stringent measures, especially the now binding P_2O_5 farm balance in case of pig farms which contribute considerably to overall organic N excretion especially in the communes with very high values. Without separation of N and P_2O_5 fractions in pig manure, the necessary P_2O_5 exports also lower the N levels on farm.

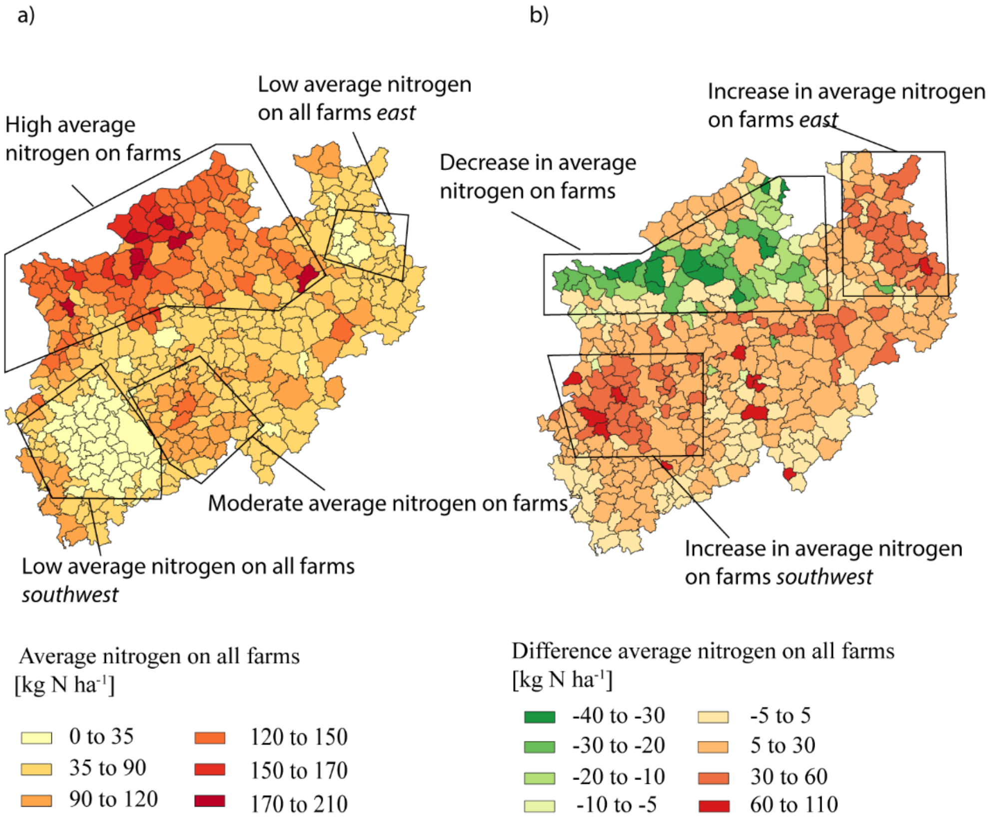

Figure 4.3: a) Simulation results for average N on communal level in kg N ha^{-1} for the FO 2007 baseline; b) Difference between the simulation results for the FO 2007 and the results for the FO 2017

Remark: Average N on farm is based on the manure excretion levels determined by livestock units from the Thuenen-Atlas and their respective excretion levels by the FO minus net-exports and plus plant-based biogas digestate in the policy scenario.

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

In line with the average N on all farms, the main manure exporting region in the baseline is found in the northwest of NRW with export levels ranging between 20 and 50 kg N ha^{-1} for communes as seen in Figure 4.4a. The primary importing region under the FO 2007 is adjacent to the south of the exporting region. Here, smaller urban districts close-by exhibit large imports per ha with up to 47 kg N ha^{-1}, whereas larger counties import between 5 to 20 kg N ha^{-1}. The net-exports of highly livestock intensive communes in counties with higher number of biogas plants increase under the revision of the FO considerably, in the range of 20 to 65 kg N ha^{-1}(Figure 4.4). Two adjacent regions in the east and the southwest of the net-exporting region, which overlap with the low average N level regions, can be identified as the major importing region. Both are dominated by arable farms and are located in counties with a moderate number of biogas plants.

Results at single farm level in the baseline (Figure 4.4c, grey bars) suggest that the majority of dairy and pig farms exports moderate amounts of N between 0 to 50 kg N ha^{-1}. Further analysis reveals that the highest values are found in pig farms with small acreages and, consequently, a high livestock density. The histogram is shifted under the FO 2017 (yellow bars). The peak for pig farms shifts to higher N exports with levels between 50 and 100 kg N ha^{-1} with many farms exceeding this range up to 250 kg N ha^{-1}. Some outliers over 250 kg N ha^{-1} relate to small and highly livestock intensive pig farms. This shift mostly reflects the binding P_2O_5 farm balance on pig farms. For dairy farms, the curve is flattening out with no notable shift in the peak. Dairy farms are mostly not affected by stricter measures under the FO 2017 besides the accounting for plant-based biogas digestate.

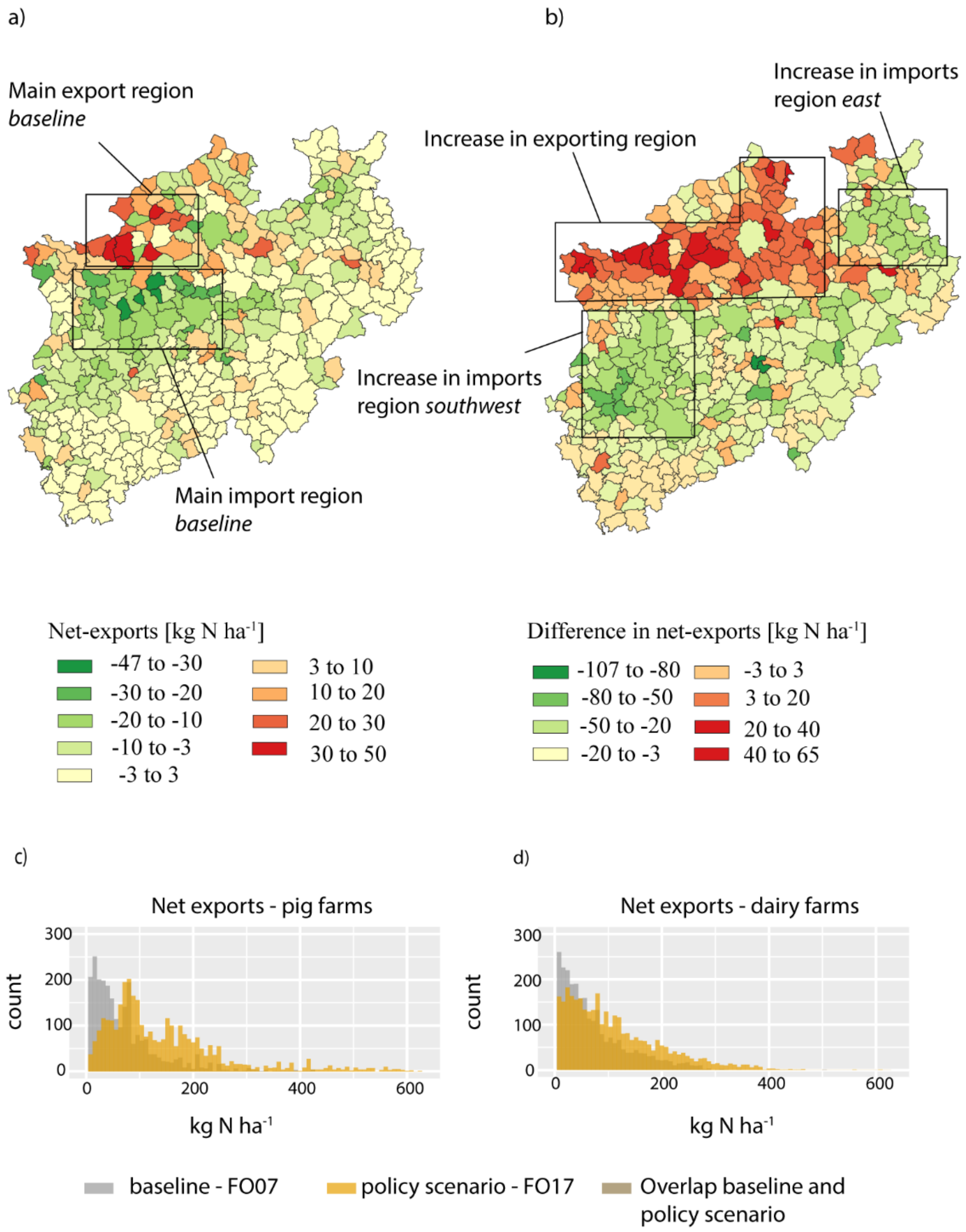

Figure 4.4: a) Simulation results for net-exports on communal level for the FO 2007; b) Difference between the simulation results for net-exports for the FO 2007 and FO 2017; Farm type specific simulation results for net exports under the FO 2007 and the FO 2017 for c) pig farms and d) dairy farms

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

The average transport distance to an importing arable farm is between 0 to 8 km as indicated in Figure 4.5a for the baseline. A cluster of communes in the northwest of NRW, relating to communes with high livestock densities, shows average transport distances up to 48 km. The largest transport distance for single pig and dairy farms is between 80 to 100 km in the baseline as seen in Figure 4.5c and Figure 4.5d. The policy scenario shows increases with up to 57 km in average transport distances. Large changes are found in communes with already high average transport distances and their neighbouring ones, as illustrated in Figure 4.5b. Some communes with high livestock densities at the border decrease their average transport distance by up to 30 km. With overall transport volumes increasing at landscape level, livestock farms in these communes cannot find anymore an arable farmer willing to import closer to 150 km. Such farms must find other compliance strategies to the FO 2017. Changes in average transport distances between dairy and pig farms do not differ much. There is an increase in smaller average transport distances compared to the baseline as some farms previously not exporting have now to export their manure. This also increases the total number of exporting farms. The average transport distance of already exporting farms is increased as well.

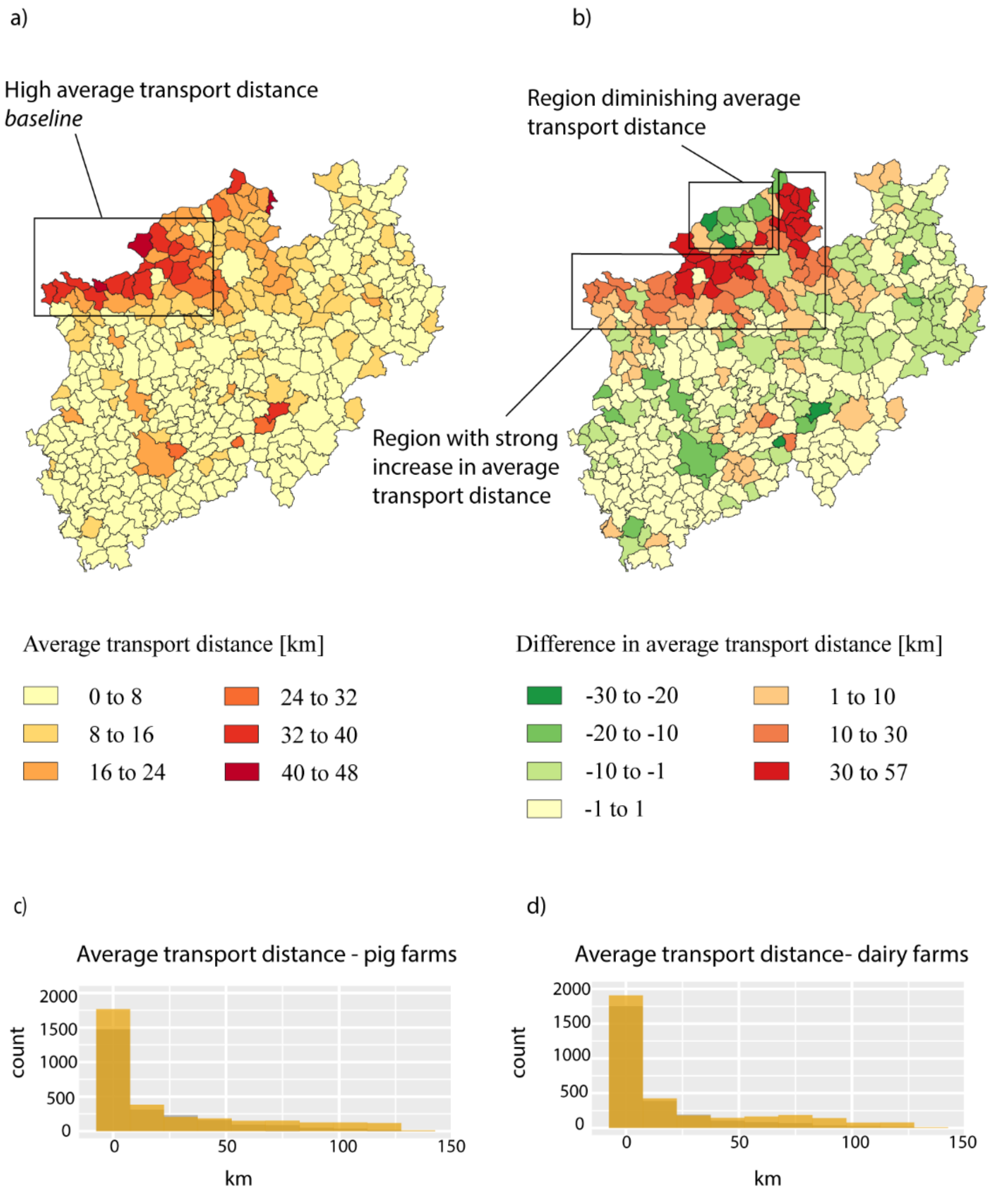

Figure 4.5: a) Simulation results for average transport distance on communal level in km for the FO 2007; b) Difference between the simulation results for average transport distance for the FO 2007 and FO 2017; Farm type specific simulation results for average transport distance under the FO 2007 and the FO 2017 for c) pig farms and d) dairy farms.

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

The remaining N absorption capacity of arable farms as reported in Figure 4.6 is defined as the amount of N imported by farms divided by the maximum amount of N that a farm may take up based on the 170 kg N ha^{-1} limit and their land endowment. Arable farms in the northwest use in almost all communes their total N absorption capacity already in the baseline. Regions which become the primary import regions under the FO 2017 use almost none of their N absorption capacity under the FO

2007. The FO 2017 scenario shows a considerably increase in the N absorption capacity outside the highly livestock intensive region were limits were already exhausted under the FO 2007. The region in the southeast of NRW shows a high increase in the share of used N absorption capacity which is primarily based on the accounting of plant-based biogas digestate and only moderate import levels.

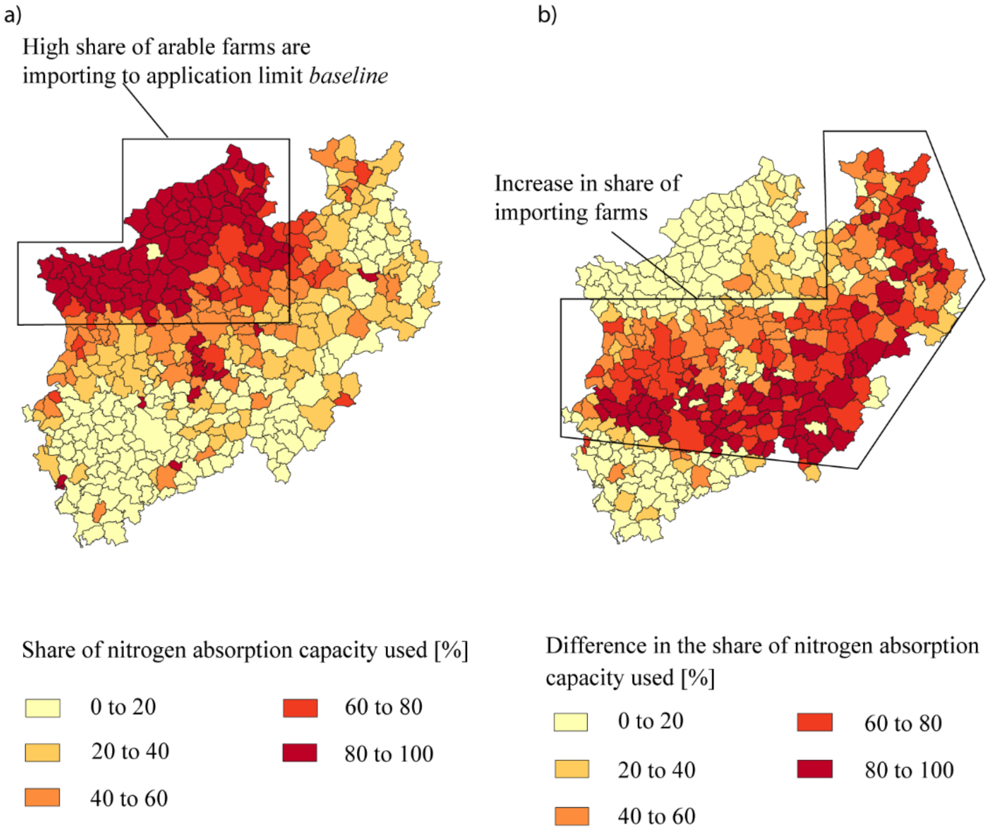

Figure 4.6: a) Simulation results for N absorption capacity on communal level in % for the FO 2007; b) Difference between the simulation results for N absorption capacity for the FO 2007 and FO 2017

Source: Own depiction with geographical data on administrative units (NUTS) retrieved from the Geoportal of the European Commission (GISCO 2018)

4.4 Discussion

4.4.1 Initialization and validation results

We included the utilized agricultural area (UAAR) in the validation (see Table 4.2) as the UAAR data from the FSS and from CORINE refer to different base years. However, we did not find notable differences. Larger differences are found with regard to livestock numbers which can be partly explained by excluding poultry, horses, sheep, and goats at single farm level in ABMSim. The omitted animal types account for 13% of the traded N in manure (LWK NRW 2018). Their excretions are however reflected in the reports above at commune level.

Baseline net-exports in the livestock intensive region tend to be underestimated compared to the official data from the nutrient report which we link to three assumptions in the model. First, we might underestimate differences in nutrient pressure inside our farm types (pig, cattle). We simulate pig fattening units of different stocking densities and sizes, but do not change the age composition (sows, piglets, fattening pigs). Similarly, we simulated dairy farms as the dominating cattle farm types, but not specialized fattening units. Any increase in the variance with regard to the N pressure for these farm types likely results in higher exports in average. Second, the estimated N export function considers implicitly also compliance strategies such as N and P reduced feeding or reducing livestock numbers, depending on the costs of exports. It is possible that the underlying cost relations disfavor exports by overestimating the costs of exports. Third, we cannot consider trade with neighboring counties in other federal states and with the Netherlands due to data and computational limitations. Therefore, some farms on the margin of the maps face large distances to find accepting farmers.

4.4.2 Simulation results

Results indicate an increase in manure transports of up to 65 kg N ha^{-1} for the most affected exporting communes due to the implementation of the FO 2017, a decrease in average N on all farms down to -40 kg N ha^{-1}, and an increase in average transport distance up to 110 km. These developments can be attributed primarily to FO 2017 measures which impact pig farms, especially the introduction of a binding P_2O_5 balance which is more restrictive for pig farms than the application limit of 170 kg N ha^{-1}. Competition on the manure market increase average transport distance for both farm types and eventually leads to higher disposal costs for dairy and pig farms. This effect was already observed in a real-world study by van Grinsven et al. (2016) for the Netherlands. Further, the increase in costs of manure disposal can be attributed to either long-distance transports as shown in this study, but also to situations where exporting farmers pay importing farmers to accept the manure. The latter cannot be simulated with the current setup of our manure market in ABMSim. Average long-distance transports might also be affected by the limited share of importing farms, as we exclude livestock farms and the so-called “fixed” farms in our study as importing agents.

Due to missing detailed information, we disaggregate data on plant-based biogas digestate from county to commune level based on maize silage acreage, and from commune to single farm based on farm size in ha. This results in an increase in manure exports for all livestock farms, even if other measures of the FO would not impact their exports. Therefore, we likely overestimate the number of exporting farms under FO 2017 while the amount of excess N within a commune and its impact on overall manure exports seems realistic. Auburger et al. (2015) used the next-neighbour approach at commune level to simulate the distribution of plant-based biogas digestate in NRW and Lower Saxony. They find that affected communes are in high livestock regions in Lower Saxony and in the northwest of NRW, only. In contrast, we find impacts in regions apart from the highly intensive livestock regions as we consider additional measures of the FO 2017 and depict a manure market with differing importing and exporting agents. On the one hand, this difference can be explained by the long-distance manure transports from the northwest, triggered by FO 2017 measures such as the P_2O_5 balance limit, which compete against emerging exporting farms in regions with low N levels. On the other hand, in Auburger et al. (2015) the additional N is distributed on all agricultural used area within a commune and only N exceeding the 170 kg N ha^{-1} is distributed in the closest communes with available absorption capacity. In our approach, however, single farms determine if they accept additional N from other farms.

4.4.3 Methodological approach

The advantage of a model at landscape level to assess potential impacts of the FO 2017 is the clear identification of nutrient hot spots and exporting and importing regions. Rather than treating administrative units as agents which exchange manure, an ABM working with individual farms considers factors such as farm type, stocking rate and distances between farms inside an administrative unit as further explanatory factors and offers a finer spatial resolution. Compared to detailed bio-economic single farm models such as in Kuhn et al. (2019), regional models including ABMs tend to simplify farm technology and representation of policy measures but account endogenously for changes in relevant parameters such as manure transport costs. However, there are distinct differences in representing manure markets in regional models. Van der Straeten et al. (2010) let single farms optimize their manure handling decision differentiating between disposal, processing, and transport options, where the costs for each option is taken from literature. The manure market is simulated as a spatial price equilibrium model where communes, consisting of aggregated farmers, are the trading entities. The model assumes a perfect market for manure exports by minimizing the manure transport costs at landscape level. In contrast, every livestock farmer in our model is able to interact with each arable farm in an auction in a distance up to 150 km. The outcome of this process is not necessarily a cost-minimal outcome for the region as a whole.

A challenge in ABMs remains the depiction of observed conditions in the baseline. There is no generally applicable (perfect) calibration mechanism as found in more traditional market equilibrium models. We neither have representative observations on manure exports of single farms nor on costs. Data on manure exchanges are only reported for counties as relatively large administrative regions. Therefore, we validate our model by aggregating over single farms to county level and find, as discussed in the previous section, a tendency to underestimate manure transports in the baseline. We face many uncertain parameters in our model such as transport costs or the actual amount of manure arable farms are willing to accept. One might in a more or less systematic trial-and-error approach try to fine tune some of the parameters to better reproduce observed data. But as these parameters which also reflect behavior might change under the policy shock, we refrained from this possibility and focused on differences between the baseline and shock.

Computational constraints remain a challenge of our “bottom-up” modeling approach at large scale. Due to reported larger transport distances already in the baseline, we need to cover a quite large landscape with thousands of farmers. This is why we opt for a meta model to depict manure export behavior. A more conventional approach is the direct use of mathematical programming (MP) models in ABMs (Balmann 1997; Happe et al. 2006; Berger 2001; Schreinemachers und Berger 2011) which drives up considerably the solution time of the ABM and typically leads to less detailed MP models compared to FarmDyn, from which our meta-model is derived. The meta-modeling approach, however, introduces additional steps such as a large-scale sensitivity analysis and cannot offer a perfect fit for all considered single farm experiments. For a comparison of the two approaches, see Seidel und Britz (2019). A challenge is that our meta-model so far only depicts manure exports but not changes in excretion quantities. The latter could result from using other compliance strategies such as N and P reduced feeding, or under high export costs, decreasing herd sizes. This is a likely a problem for those farms which cannot find a partner for manure exports due to the 150 km distance restrictions as reflected in our results. Alternatively, one could either estimate a profit function which determines simultaneously changes in herd sizes and in the value of nutrient emission rights, similarly to Seidel und Britz (2019) for the case of the land endowment or as in van der Straeten et al. (2011) determine the amount of N excretion for a given amount of nutrient emission rights. Other advances to depict multiple input output relations on farm level are made in the area of machine learning which is able to depict more elements of farm behaviour given a large enough data set to identify the meta-model (Storm et al. 2020).

4.4.4 Policy implications

Our modeling approach allows to assess the impact on nutrient loads on farms and communes by the implementation of all relevant FO 2017 measures. By introducing the FO 2017 measures on farm level and biogas digestate on communal level, our results help identifying the most affected communes both on the importing and exporting side on the manure market. The results can contribute not only to the discussions on targeted assistance for exporting farmers to alleviate the increasing cost burden but also to enhance the infrastructure required to apply manure in regions dominated by arable farms with low manure storage capacities. Further, the identification of the most affected communes help implements targeted risk-based control schemes for non-compliant farmers.

Our results indicate a large increase in manure transports and movement of nutrients due to the implementation of the FO 2017. However, the European Commission raised the issue that even the imposed measures will not be able to reduce N levels in the most affected regions. Hence, the German government implemented a new FO in the year 2020 with even stricter measures, especially in regions which are marked as red zones with nitrate (NO_3^-) exceeding the level of 50 mg l^{-1} in ground water bodies (BMEL 2020). This entails, for example, a reduction of N application limits of 130 kg N ha^{-1} for farms as a state specific measure in NRW. As the red zones are not cohesively distributed over the whole of NRW, compared to more regional approaches, our “bottom-up” approach would help to improve the understanding of the potential impacts on regional nutrient distribution to deliver more tailored solutions for the most affected farms.

Another aspect to consider by policymakers related to increased manure transport distances and volumes are environmental impacts such as a rise in emissions and noise. Studies suggested that the application of odor in regions not accustomed to livestock farming is a hurdle to accept manure (Case et al. 2017; Núñez und McCann 2004) and thus has to be considered in the elaboration of regional specific policy support.

4.5 Conclusion

This study simulates manure transports induced by the revised FO as the key legal framework to implement the EU ND and the WFD in German agriculture. It covers the whole state of NRW, using the ABM ABMSim. A meta-modeling approach depicts decision behavior for individual farms, considering the heterogeneity of the farm population inside the case study region. The meta-model is estimated from simulating optimal compliance strategies at single farm level in a large-scale representative sample with a quite detailed bio-economic model, considering different cost of manure export and the various policy measures in detail. The meta-model approach overcomes computational limitations in other ABMs working with single farms and allows depicting a population with over 30.000 agents and a landscape with almost 35.000 km². This allows for the identification of export- and import regions, N hotspots, most affected farm types, and the distribution of changes in indicators at farm level. This underlines its potential, for instance, to assess the national implementation of or similar policies in other regions.

Results indicate that further manure transports are primarily triggered by the new FO measure which prevents P_2O_5 surpluses, affecting mostly pig farms. It leads to larger increases in manure export quantities and distances, up to 110 km on average for communes dominated by pig farms, and in reduced organic N levels. Even though nitrogen thresholds are not binding for most dairy farms, they also face in average higher transport costs due to the competition with pig farms. This also reflects that N in plant-based biogas digestate is accounted now in the new FO, decreasing the N absorption capacities of importing farms and communes. Further work could expand the framework to a meta-modeling approach which also considers adjustments in excretion quantities.

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Appendix

Appendix Chapter 2

Appendix 2.1: Investment costs by investment horizon and credit rates

	150 kW	250 kW	500 kW
Investment horizon - 20 years ['000 Euro]	554	721	1246
Investment horizon - 10 years ['000 Euro]	173	252	359
Investment horizon - 7 years ['000 Euro]	214	290	372
Credit rate - 2 years [%]		3.5	
Credit rate - 5 years [%]		4	
Credit rate - 10 years [%]		4.5	
Credit rate - 20 years [%]		5	

Source: (KTBL 2013, 2014; Fachagentur für Nachwachsende Rohstoffe e.V. 2013)

Appendix 2.2: Production related biogas plant specific parameters

	250 kW	500 kW
Electric conversion efficiency [$\%$]	37	40.1
Heat conversion efficiency [$\%$]	44	43.2
Net-Volume fermenter [m^3]	1800	3400
Digestion load [$\frac{kg}{day*m^3}$]	2.5	2.5
Dwelling time [day]	97	97

Source: (KTBL 2013; Fachagentur für Nachwachsende Rohstoffe e.V. 2009)

Appendix 2.3: Substrate specific parameters

	Manure	Grass silage	Maize silage
Dry matter content [$\%$]	10	35	33
Organic dry matter content [$\%$]	80	90	95
Methane yield [$\frac{Nm^3}{t}$]	14	98	106

Source: (KTBL 2013; Fachagentur für Nachwachsende Rohstoffe e.V. 2009)

Appendix 2.4: Parameter for variable cost calculation

Required electricity *[% of el. production*]	7
Electricity purchasing price [$\frac{cent}{kWh}$]	19
Maize silage [$\frac{€}{ton}$]	36
Gras silage [$\frac{€}{ton}$]	33

(KTBL 2013; Fachagentur für Nachwachsende Rohstoffe e.V. 2009)

Appendix Chapter 3

Appendix 3.1: Variables and parameter in the upper and lower problem and their definition

Variable/Parameters	Upper Problem	Lower Problem	Definition
fit	X (objective)	0	mean squared relative difference observed and estimated nitrogen transports
transAC	0	X (objective)	
$f_{co,co'}$	X	O	nitrogen transports between counties
$f_{c,c'}$	O	X	nitrogen transports between communes
of	^	O	observed nitrogen transports
transC	X	^	estimated transport costs per kg of nitrogen
tcD,tcS,tcR	X	^	distance related transport costs (D = linear, S = quadratic, R = square root)
tcH	X	^	transport handling costs for nitrogen
d	^	^	distance between two communes
p	X	^	marginal price of nitrogen use
s	X	X	nitrogen use
ha	^	^	agricultural used land
q	^	^	excreted manure quantity net of storage and application losses in tons of nitrogen
Sets			Definition
c			communes
co			counties
c_co			affiliation of communes to a certain county
b			biogas digestate
se			sewage
o			other sources

X – defines a variable as a decision variable in the problem level; ^ - indicates that a variable is either fixed or an exogenous parameter in the problem level; 0 – indicates that the variable is not occurring the problem level

Appendix Chapter 4

Appendix 4.1: Explanatory factors of the meta model and corresponding ranges

Explanatory factors	Farm type	Min	Median	Max	Data Source
Farm size [ha]	Dairy	8.14	61,24	221.35	FSS[a]
	Pig fattening	6.84	48.20	159.05	
Livestock density [LU ha^{-1}]	Dairy	0.63	1.75	5.94	FSS[a]
	Pig fattening	1.11	2.06	14.82	
Grassland share [%]	Dairy	0.06	0.51	1	FSS[a]
Milk price [€ kg^{-1} milk^{-1}]	Dairy	29.00	33.00	37.00	KTBL[b]
Pork price [€ kg^{-1} carcass weight^{-1}]	Pig fattening	1.30	1.45	1.60	KTBL[b]
P-enriched soils [0-1]	Pig fattening	0	1	1	(Osterburg und Techen 2012)
Manure Export Cost [€ $^{m-3}$]	Dairy and pig fattening				(Auburger et al. 2015)
Manure storage capacity [m]	Dairy and pig fattening	6.00	8.00	8.00	FSS[a]

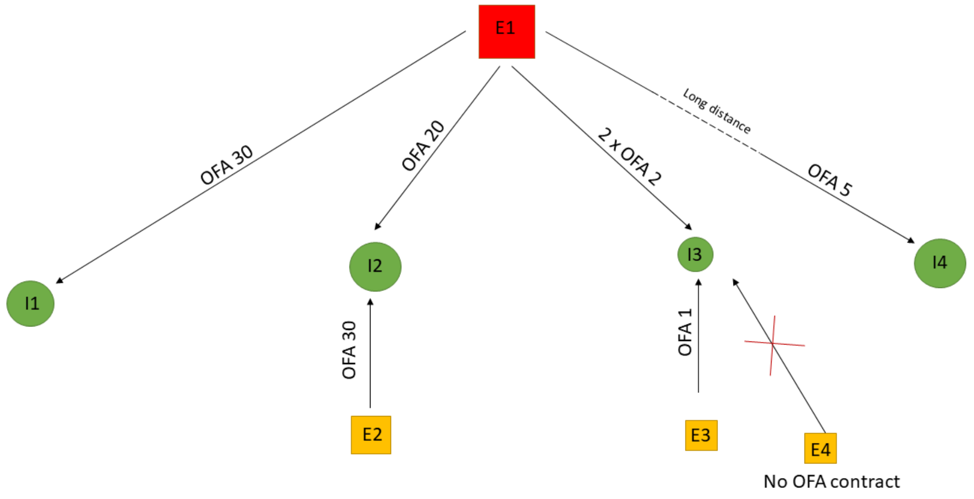
Remark: [a] detailed source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [b] KTBL

Appendix 4.2: Meta-Modeling Results

Explanatory factors	Dairy FO 2007	Dairy FO 2017	Pig FO 2007	Pig FO 2017
Intercept	-3821.99	-3806.82	1037.75	139.42
nTotLand_sqrt			-267.00	-201.47
shareGrassLand_sqrt				
LUperHa_sqrt		-2563.62	119.28	72.83
monthManStore_sqrt			40.42	18.33
soilSharePenriched_sqrt			1.61	126.67
costsManureExport_sqrt			-378.15	-36.77
nTotLand^2	-0.05	-0.05	-0.06	-0.049
shareGrassLand^2	132.19	129.34		
LUperHa^2	1.05	21.29	0.24	0.74
monthManStore^2	0.39	0.53	-0.21	
milkPrice^2	-0.23	-0.56		
porkPrice^2			-124.44	107.25
soilSharePenriched^2			35.88	226.48
costsManureExport^2	-0.31	-0.32	-1.18	-0.12
nTotLand_log	-831.09	-828.61		
shareGrassLand_log	33.93	27.15		
LUperHa_log	85.06	1758.36		
monthManStore_log	101.49	156.69		
milkPrice_log	1793.79	2541.51		
costsManureExport_log	-85.86	-92.64		
nTotlandXshareGrassland	-0.18	-0.33		
nTotlandXsoilSharePenriched			-0.33	0.44
nTotlandXLUperHa	17.1	17.18	9.29	9.35

nTotlandXmonthManStore	-0.1	-0.08	-0.05	-0.03
nTotlandXmilkPrice	-4.1	-0.31		
nTotlandXporkPrice				
nTotlandXcostsManureExport	-0.37	-0.01	-0.03	-0.01
shareGrassLandXLUperHa	-10.33	-0.29		
shareGrassLandXmonthManStore	0.78	0.39		
shareGrassLandXmilkPrice	-4.1	-4.79		
shareGrassLandXcostsManureExport	-0.37	0.55		
LUperHaXmonthManStore	0.78	0.45	0.08	0.04
LUperHaXmilkPrice	-1.22	0.17		
LUperHaXcostsManureExport	0.47	0.06	-0.13	0.25
LUperHaXsoilSharePenriched			1.56	1.26
LUperHaXporkPrice			-12.23	-17.89
monthManStoreXmilkPrice	-0.26	-0.6		
monthManStoreXcostsManureExport	0.03	0.03	0.10	-0.01
monthManStoreXsoilSharePenriched			0.54	0.39
milkPriceXcostsManureExport	0.47	0.51		
porkPriceXcostsManureExport			58.2	4.82
soilSharePenrichedXporkPrice			-26.28	-212.17
soilSharePenrichedXcostsManureExport			1.13	-0.21

Appendix 4.3: Examples of the most relevant manure market implications emerging in the manure auction mechanism.



Remark: E – exporting agents, I – importing agents, OFA – organic fertilizer contracts

In the above figure, we show exemplary the most important implications for the results of the auction mechanism and the related assumptions described above. Exporting farms are rectangular and marked with an E whereas importing farms are shown as circles marked with an I. The size of the shape is in accordance with its hectare size, thus the larger the shape the larger the farm size. The color distinction for exporting farmers indicates different livestock densities with red having a high livestock density and thus a large manure export need whereas orange indicate lower livestock densities. E1 is a large exporting farm with a high livestock density. In the first case, E1 wins an MA 30 contract of I1 at the auction, thus E1 can export 30 barrels to the large arable farm I1. In the second case, I2 is a large arable farm which offers an MA 30 and an MA 20 on the manure market. As E2 is closer than E1 to I2 it wins at the auction the MA 30 whereas E1 only gets the MA 20 contract. In the third case, the arable farm I3 is small thus only offering smaller contracts. As E3 and E4 only have to get one MA they do not bid on the MA 2s offered by I3. Hence, E1 get two MA 2s and E3 gets one MA as it is closer to I3 than E4. Eventually, E4 does not get rid of its excess manure. In the fourth case, we see that E1 is far away from the importing farm I4 which increases the transport costs and therefore reduces the amount E1 is willing to export to farm I4. Hence, E1 is only bidding on an MA 5 which it wins in the auction.