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*David Schäfer, Wolfgang Britz, Till Kuhn*

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Editor: Thomas Heckelei
Institute for Food and Resource Economics
University of Bonn
Nußallee 21
53115 Bonn, Germany

Phone: +49-228-732332
Fax: +49-228-734693
E-mail: thomas.heckelei@ilr.uni-bonn.de

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## Abstract

ABMSIM, an agent-based model, 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, 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 $P_2O_5$ 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
**JEL classification: Q18, C63, Q52**

## 1 Introduction

In the European Union, the Nitrates Directive (NiD) and Water Framework Directive (WFD) are the primary policies to prevent nitrogen (N) and phosphorus ($P_2O_5$) losses from agricultural sources to the environment (European Council 1991). The national implementation of the NiD 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 so-called Fertilization Ordinance (FO) as the implementation of the NiD in 2017 after infringement proceedings by EU Commission. The EU Commission judged this revision still insufficient to meet the target of the NiD in German ground and surface water bodies. The German government has therefore decided on 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 NiD 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 and 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 cost which are exogenous in farm modelling but are likely changing when manure trade increases at landscape level.

This motivates the application of regional manure market models, such as the Spatial Equilibrium (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 agent-based model (ABM). ABMs 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, whereas SPE models have to assume transport costs minimization in perfect markets, 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 or more kilometres apart are frequently observed (LWK NRW 2018). ABMs which depict decision behaviour based on mathematical programming models specified for each single farm (Happe et al. 2011; Troost and Berger 2015) covered so far only smaller regions of maximal 1700 km$^2$ (Huber et al. 2018) due to computational restrictions. The alternative approach working 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, generating 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 Farm Structure Survey (FSS) and other statistical data using a highest-posterior density estimator (HPD) (Heckelei et al. 2008). This captures the spatial distribution of important farm characteristics at commune level while complying with data protection laws, in here for a population of ~34.000 farms for all 396 communes of the German state North Rhine-Westphalia (NRW). Second, we overcome computational limitations based on a meta-modelling approach (Lengers et al. 2014; Seidel and Britz 2019) which replaces the programming models for each farm used in other agricultural ABM. 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 German Fertilization Ordinance 2017 (FO 2017) on state level (34.098 km$^2$). The resulting insights into impacts of measures of the German NiD 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.

## 2 Methods

We apply the agent-based model ABMSIM to analyze the impacts of the revised FO on manure transports and nitrogen distribution in NRW. This chapter presents the relevant features of ABMSIM for the manure market (section 2.1), the underlying farm typology (section 2.2), followed by the key steps in the initialization and the location of farmsteads in space (section 2.3). Further, it introduces important features in the context of manure transports such as the meta-modelling approach with FarmDyn to generate the decision behavior of manure exporters (section 2.4). Eventually, we describe the theoretical framework of the manure market in ABMSIM and the policy implementation (section 2.5).

### 2.1 *Agent-based model ABMSIM*

ABMSIM is an agent-based model 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 imported 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.

### 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- and 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 Farm Structural Survey database (FSS). 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. Further, farms are differentiated by size class in hectares in accordance with classifications available in the FSS (IT NRW 2018).   shows a complete list with all farm specific characteristics relevant for the manure market and the corresponding sources.

Table 1: Overview on relevant characteristics on the manure market for individual farms

| *Characteristics* | *Description* |
|---|---|
| Location | Spatially explicit with affiliation to commune and county |
| Farm type | One of the following farm types: arable, dairy, pig fattening, fixed |
| Size class | One of the following size classes [ha]: <5, 5-10, 10-20, 20-50, 50-100, 100-200, >200 |
| 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 nitrogen on farm [kg] |
| Manure export estimation function | Manure export estimation function is only valid for farms with livestock |

### 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 1 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 (Lanwirtschaftskammer 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 and 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 07 and FO 17 (BMEL 2017, 2007).

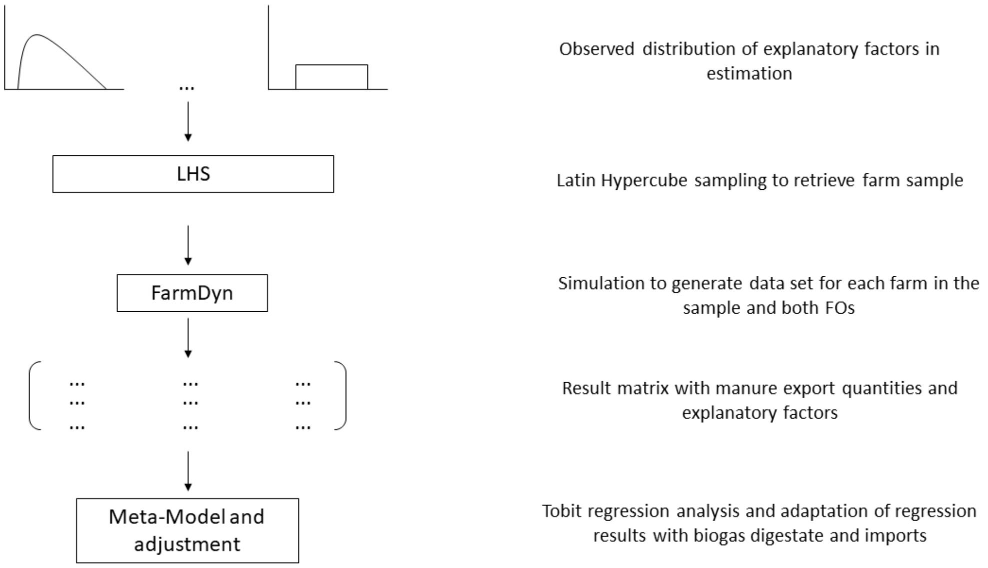
Fourth, the remaining farm characteristics used in the meta-modelling approach to estimate manure exports such as the P soil status and manure storage capacities are distributed. The manure storage capacities are distributed using a Latin Hypercube sampling approach with a range taken from (Osterburg 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).

### 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 and is illustrated in Figure 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-modelling 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 1.

Figure 1: Meta-Modelling 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 07 and the FO 17 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 P2O5 application limits, and required manure storage. For a complete list and description of the FO 17 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 17. In the FO 07, plant-based digestate was not accounted for in the nitrogen 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 2.

### 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 (MA). 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 $21m^3$ 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 barrels, which are traded in the auction starting with the largest contracts. The number of contracts and their size of an importing farmer is offering 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, the farm P2O5-balance is binding in the application of organic fertilizer due to FO measures (Kuhn et al. 2019), we assume that the P2O5-supply soils in arable farms is mostly low and is therefore not considered in the nutrient uptake capacity.

Exporting farms bid on the MA contracts offered by importing farmers up to distance of 150 km. The distance between the exporting and importing farm determines the transport costs for the MA. The export function determines based on the specific costs each MA along with farm specific factors the profit maximal manure export quantity (see section 2.4 and Appendix 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 07 and FO 17. As shown by the study of (Kuhn et al. 2019) this relates mainly to a P2O5-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 P2O5 enriched soils .Other adaptations of importing farmers or P2O5-balances are assumed to be not of relevance for arable farms which constitute the importing site of the manure market in ABMSIM.

Offering MA 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 3 gives further detail on the auction mechanism.

## 3 Results

This section assesses the impact of the revised FO 17 compared to the FO 07 on manure transports and nitrogen at landscape level for the state of NRW in Germany. Before, 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 07 with available data on observed manure transports (LWK NRW 2018). The simulation for FO 17 accounts also for plant-based biogas digestate and are based on an updated manure export function for each livestock farmer to the FO 17.

### 3.1 *Initialization and validation of the manure market*

Table 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 nitrogen excretion according to the FO as derived from the Thuenen-Atlas is considered when reporting nitrogen 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 2.

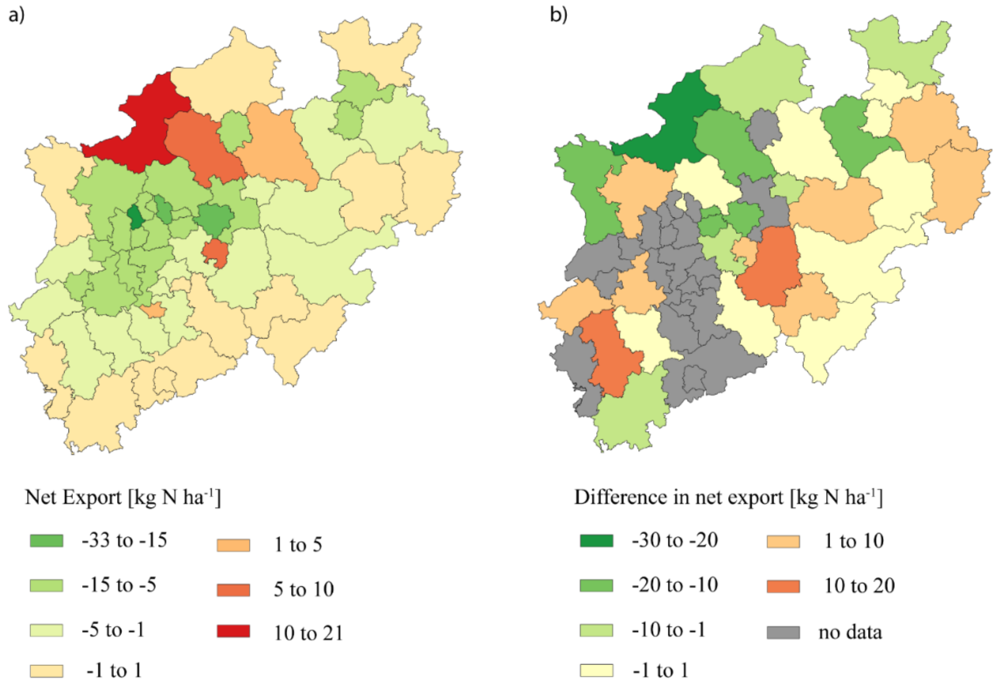
Table 2: Initialization results for land-use, livestock, and number of farms for NRW

| | 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 2 shows net exports for each county as simulated for the FO 07 as (a) 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 4.1.

Figure 2: a) Net exports in the baseline under the FO 07; b) Difference in net exports between FO 07 and nutrient report 2016 (LWK NRW XXX)



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

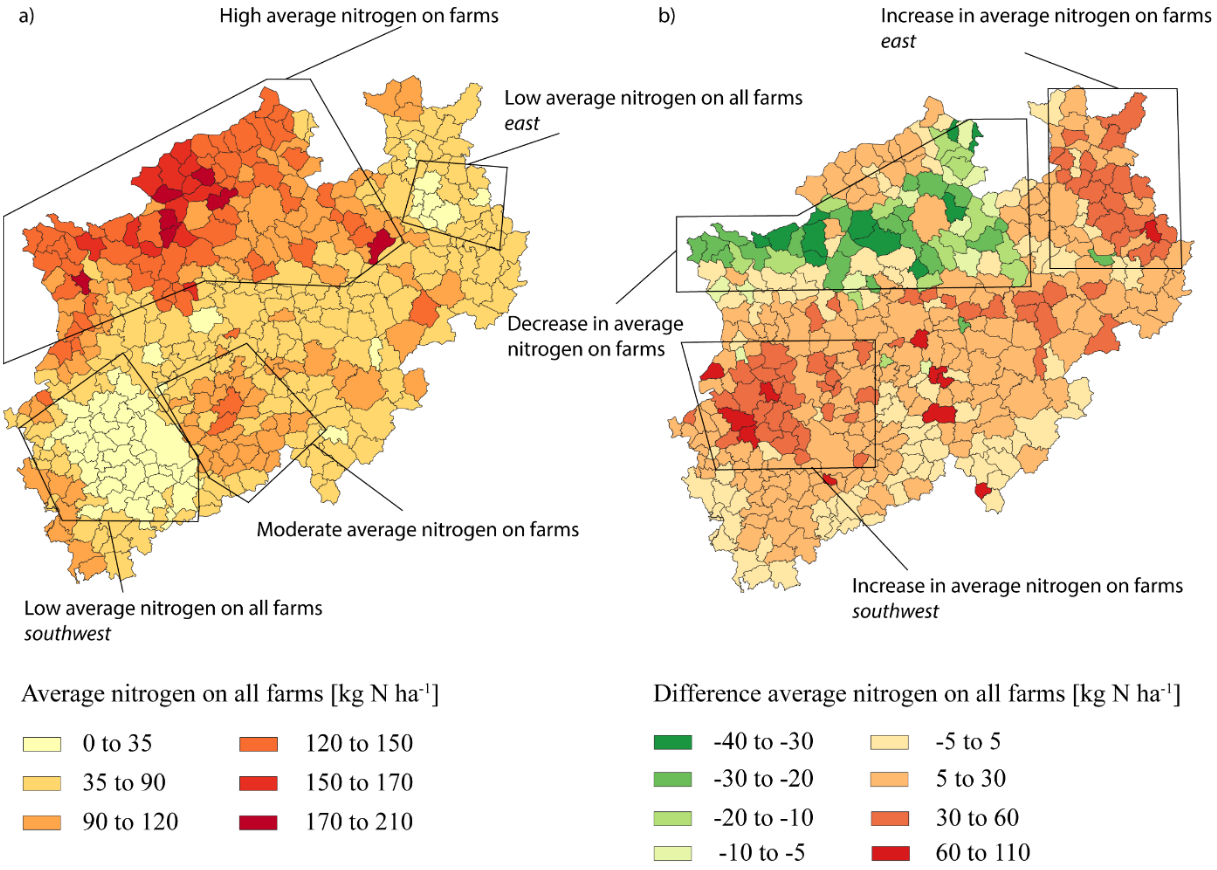
### 3.2 *Simulation results*

Figure 3 shows simulated average remaining organic nitrogen per commune, aggregated from single farm level. It depicts organic nitrogen availability as the sum of manure excretion of all animals as reported in the Thuenen-Atlas plus plant-based biogas digestate for the FO 17 minus simulated net-exports. Baseline results (figure 3a, relating to FO 07, i.e. without plant-based biogas digestate) show regions with higher than average organic nitrogen 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 nitrogen 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 nitrogen 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 17 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 nitrogen levels up to 140 kg N $ha^{-1}$. This reflects both the accounting of plant-based biogas digestate under the FO 17 and higher imports in these regions dominated by arable farming. Note again that so-called fixed farms and livestock farms cannot import manure in our simulations.

In the previously high average nitrogen region, the results show a decrease in organic nitrogen 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 nitrogen 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 nitrogen levels on farm.

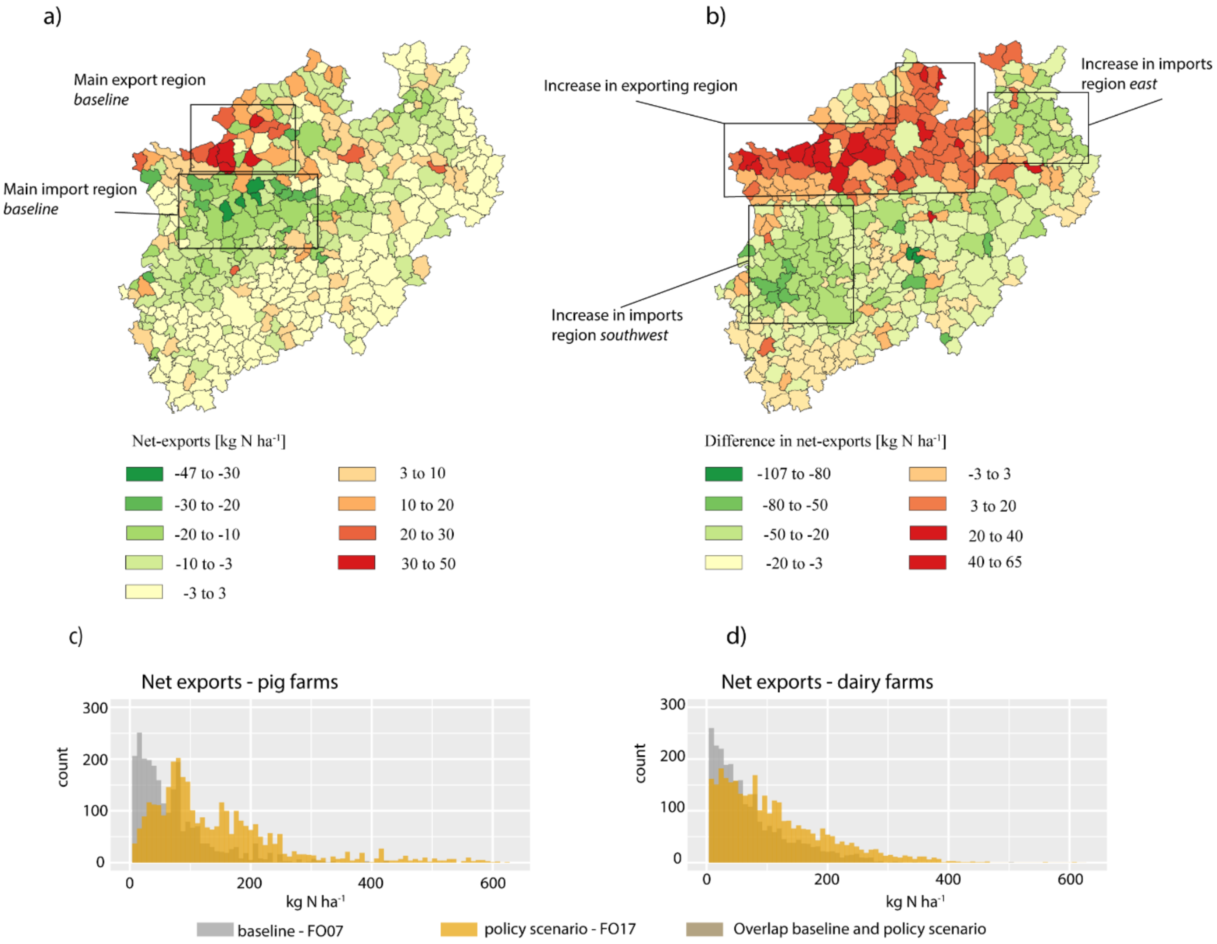
Figure 3: a) Simulation results for average nitrogen on communal level in kg N ha$^{-1}$ for the FO 07 baseline; b) Difference between the simulation results for the FO 07 and the results for the FO 17



Remark: Average nitrogen 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.

In line with the average nitrogen 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. The primary importing region under the FO 07 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$^{-1}$. Two adjacent regions in the east and the southwest of the net-exporting region, which overlap with the low average nitrogen 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.

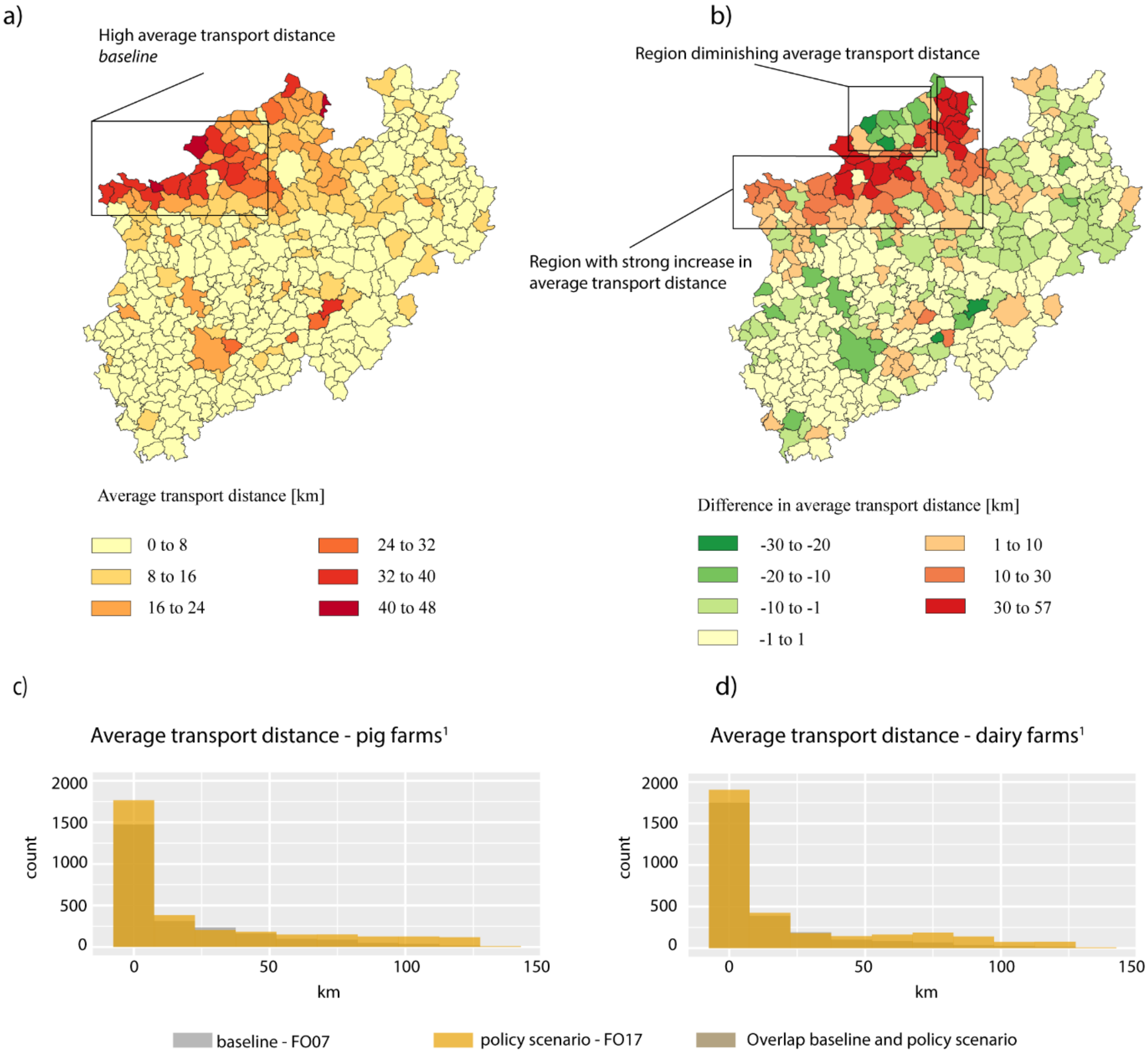
Figure 4: a) Simulation results for net-exports on communal level for the FO 07; b) Difference between the simulation results for net-exports for the FO 07 and FO 17; Farm type specific simulation results for net exports under the FO 07 and the FO 17 for c) pig farms and d) dairy farms.



Results at single farm level in the baseline (figure 4c, grey bars) suggest that the majority of dairy and pig farms exports moderate amounts of nitrogen between 0 to 50 kg N ha$^{-1}$. Further analysis reveals, as expected, 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 17 (yellow bars). The peak for pig farms shifts to higher nitrogen 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 17 besides the accounting for plant-based biogas digestate.

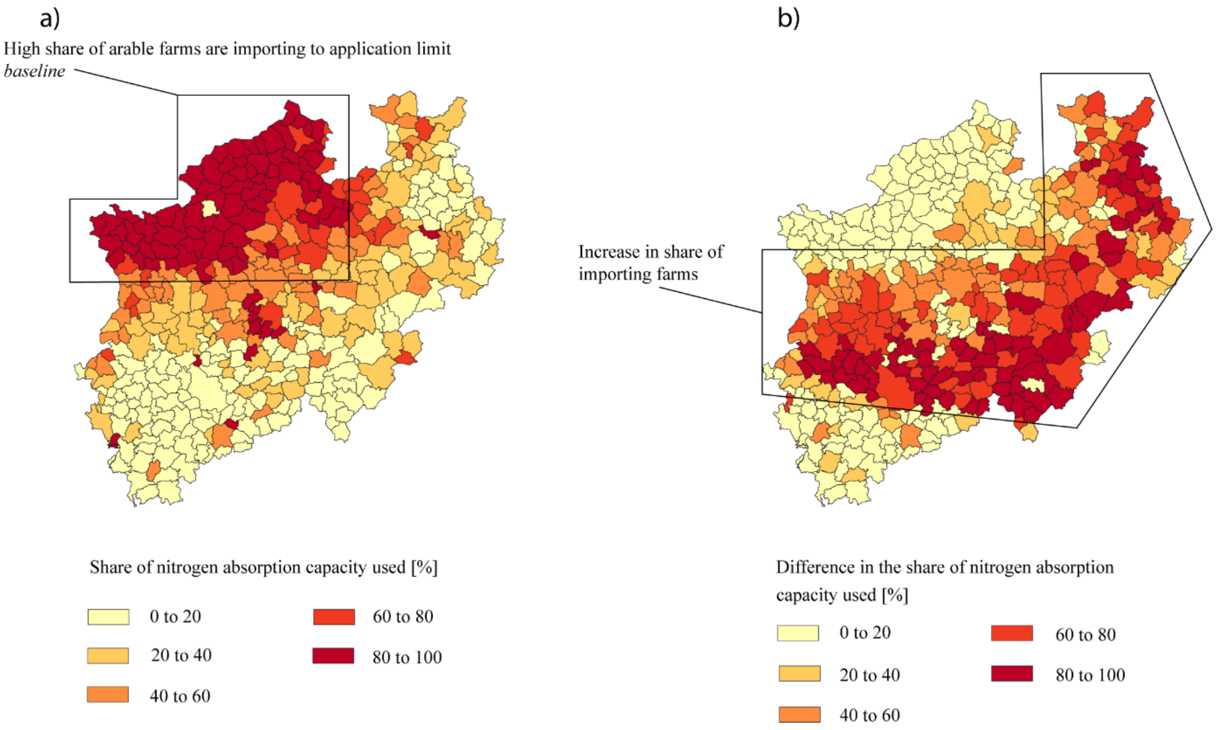
The average transport distance to an importing arable farm is between 0 to 8 km as indicated in figure 5a) for the baseline. A cluster of communes in the northwest of NRW, relating to communes with high livestock densities, shows average transport distances up to 48 km. The largest transport distance for single pig and dairy farms is between 80 to 100 km in the baseline as seen in figure 5 c) & d). 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 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 17. 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 distances of already exporting farms is increased as well.

Figure 5: a) Simulation results for average transport distance on communal level in km for the FO 07; b) Difference between the simulation results for average transport distance for the FO 07 and FO 17; Farm type specific simulation results for average transport distance under the FO 07 and the FO 17 for c) pig farms and d) dairy farms.



The remaining nitrogen absorption capacity of arable farms as reported in Figure 6 is defined as the amount of nitrogen imported by farms divided by the maximum amount of nitrogen 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 nitrogen absorption capacity already in the baseline. Regions which become the primary import regions under the FO 17 use almost none of their nitrogen absorption capacity under the FO 07. The FO 17 scenario shows a considerably increase in the nitrogen absorption capacity outside the highly livestock intensive region were limits were already exhausted under the FO 07. The region in the southeast of NRW shows a high increase in the share of used nitrogen absorption capacity which is primarily based on the accounting of plant-based biogas digestate and only moderate import levels.

Figure 6: a) Simulation results for nitrogen absorption capacity on communal level in % for the FO 07; b) Difference between the simulation results for nitrogen absorption capacity for the FO 07 and FO 17



## 4 Discussion

### 4.1 *Initialization and validation results*

We included the utilized agricultural area (UAAR) in the validation (see Table 2) as the UAAR data from the FSS and from CORINE refer to different base years but found not notable differences. Larger ones 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 nitrogen 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 pressures 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 nitrogen pressure for these farm types likely results in higher exports in average. Second, the estimated nitrogen 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. Some farms on the margin of the maps face therefore large distances to find accepting farmers.

### 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 the implementation of the FO 17, a decrease in average nitrogen 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 17 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 transport 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 dis-aggregate 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. We therefore likely overestimate the number of exporting farms under FO 17 while the amount of excess nitrogen within a commune and its impact on overall manure exports seems realistic. Auburger et al. (2015) using the next-neighbour approach at commune level simulate the distribution of plant-based biogas digestate in NRW and Lower Saxony and find affected communes in high livestock regions in Lower Saxony and in the northwest of NRW, only. We find impacts in regions apart from the highly intensive livestock regions as we consider additional measures of the FO 17 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 17 measures such as the $P_2O_5$ balance limit, which compete against emerging exporting farms in regions with low nitrogen levels. On the other hand, in Auburger et al.

(2015) the additional nitrogen is distributed on all agricultural used area within a commune and only nitrogen exceeding the 170 kg N $ha^{-1}$ is distributed in the closest communes with available absorption capacity, whereas in our approach single farms determine if they accept additional nitrogen from other farms.

### 4.3 *Methodological approach*

The advantage of a model at landscape level to assess potential impacts of the FO 17 is the clear identification of nutrient hot spots and ex- 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 also 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. There are, however, 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 150km. 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. We therefore 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 focus on differences between the baseline and shock.

Computational constraints remain a challenge of our “bottom-up” modelling 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 (MPs) 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 MPs compared to FarmDyn, from which our meta-model is derived. The meta-modelling 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 and Britz (2019). A challenge in here 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 very high export costs, decreasing herd sizes. This a likely a problem in our results for those farms which cannot find a partner for manure exports due to the 150 km distance restrictions. Alternatively, one could similarly to Seidel and Britz (2019) for the case of the land endowment, estimate a profit function which determines simultaneously changes in herd sizes and in the value of nutrient emission rights, 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 s 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 *Policy implications*

Our modelling approach allows assessing the impact on nutrient loads on farms and communes by the implementation of all relevant FO 17 measures. By introducing the FO 17 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 huge increase in manure transports and movement of nutrients due to the implementation of the FO 17. However, the European Commission raised the issue that even the imposed measures will not be able to reduce nitrogen 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 exceeding the level of 50 mg $l^{-1}$ (BMEL 2020). This entails, e.g., a reduction of nitrogen 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 policy maker connected to increased manure transport distances and volumes are environmental impacts such as a rise in emissions and noise linked to transport. Studies also 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.

## 5 Conclusion

This study simulates manure transports induced by the revised German Fertilization ordinance as the key legal framework to implement the EU Nitrate directive and the Water Framework Directive in German agriculture. It covers the whole state of North Rhine-Westphalia (NRW), using the agent-based model (ABM) ABMSIM. A meta-modelling 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, nitrogen 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 nitrogen levels. Even though nitrogen thresholds are not binding for most dairy farms, they also face in average higher transport costs due to competition with pig farms. This also reflects that nitrogen in plant-based biogas digestate is accounted now in the new FO, decreasing the nitrogen absorption capacities of importing farms and communes. Further work could expand the framework to a meta-modelling approach which also considers adjustments in excretion quantities.

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## Appendix

*Appendix A*: Explanatory factors of the meta model and corresponding ranges

| Explanatory factors | Farm type | Minimum | Median | Maximum | 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] |

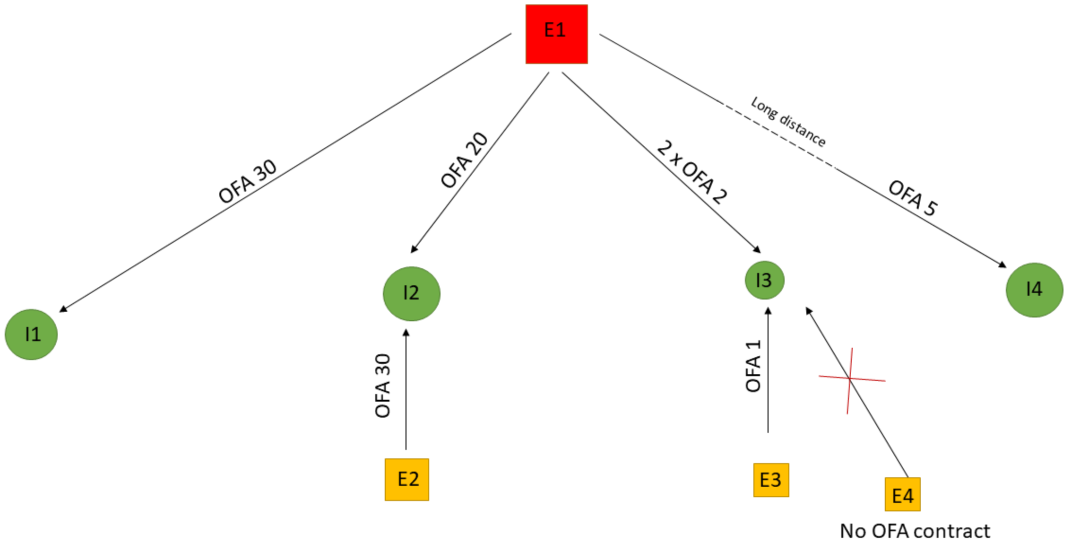
Remark: [a] detailed source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [b] KTBL

*Appendix B*: Meta-Modelling 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 C*: 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 figure X 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 indicate 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.