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The revision of the German Fertilization Ordinance in 2017: Analyzing economic and environmental impacts at farm-level

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Abstract

The Fertilization Ordinance (FO), implementing the EU Nitrates Directive in Germany, is the core regulation to limit the loss of reactive nitrogen and phosphorus from agriculture. It was revised in June 2017 after environmental targets have been missed. The revised FO contains considerable tighter measures such as stricter nutrient application thresholds and the mandatory use of low-emission manure application techniques. The aim of this thesis is to assess the economic and environmental impact of the revision at farm-level, focusing on Northwest Germany. To do so, a bio-economic farm model is applied to the pig fattening and dairy farm population of North Rhine-Westphalia and, in combination with a crop modelling framework, to dominant farm types selected from a generated typology. The model covers the measures of the FO as well as prominent compliance strategies. Manure transport as a central adaption strategy to meet stricter nutrient application thresholds is additionally evaluated in a life cycle assessment. On-farm compliance costs are highly heterogeneous and range from 0 to 2.66 Euro per pig for pig fattening farms and from 0 to 0.83 cent per kg milk for dairy farms. 47% of pig fattening and 38% of dairy farms do not face any costs. High compliance costs are found for pig fattening farms with high stocking densities, which need to fulfill the stricter phosphate surplus restrictions of the FO 2017. In contrast, dairy farms almost solely face costs for the compulsory use of low-emission manure application techniques. Intensive pig fattening farm types with a high stocking density reduce nitrate and ammonia losses considerably, which is mainly due to the export of excess manure, the shift of manure application from autumn to spring, and the use of low-emission manure application techniques. Less intensive pig fattening farm types, representing a high share of the pig stock, realize only little emission reduction. Arable farm types, starting to import manure under the FO 2017, can save variable costs by replacing chemical fertilizer. As a consequence, nitrate and ammonia losses increase, which illustrates the danger of regional pollution swapping due to manure imports. However, manure transport from livestock to arable farms can realize a net-reduction of all assessed environmental impacts. The heterogeneous impact of the FO 2017 makes it necessary to precisely target enforcement mechanisms as well as supporting measures at the affected farms. Furthermore, policymakers need to protect sensitive areas from the negative effect of manure imports.

Zusammenfassung

Die Düngeverordnung (DüV) implementiert die EU-Nitratrichtlinie in Deutschland und ist die zentrale Regulierung, um den Verlust von reaktivem Stickstoff und Phosphor aus der Landwirtschaft zu verringern. Sie wurde im Juni 2017 novelliert, nachdem verschiedene Umweltziele nicht erreicht wurden. Die überarbeitete DüV beinhaltet deutlich strengere Maßnahmen, wie zum Beispiel eine stärker limitierte Nährstoffausbringung oder die verpflichtende Nutzung von emissionsarmer Technik zur Wirtschaftsdüngerausbringung. Diese Dissertation untersucht die ökonomischen und ökologischen Effekte der Novelle in Nordwestdeutschland. Dazu wird ein bio-ökonomisches Betriebsmodell sowohl auf die gesamte Population von Schweinemast- und Milchviehbetrieben in Nordrhein-Westfalen als auch, in Kombination mit einem Pflanzenwachstumsmodell, auf typische Betriebe angewandt. Der Export von Wirtschaftsdünger, als wichtige Anpassung an strengere Vorgaben an die Nährstoffausbringung, wird darüber hinaus in einer Lebenszyklusanalyse untersucht. Die betrieblichen Anpassungskosten sind stark heterogen und reichen von 0 bis 2,66 Euro pro Schwein für Schweinemastbetriebe und von 0 bis 0,83 Cent pro kg Milch für Milchviehbetriebe. 47% der Schweinemast- und 38% der Milchviehbetriebe haben keinerlei Anpassungskosten. Schweinemastbetriebe mit hohem Tierbesatz sind hohen Kosten ausgesetzt, um den geringeren zulässigen Phosphatüberschuss unter der DüV 2017 einzuhalten. Für Milchviehbetriebe hingegen entstehen vor allem Kosten durch die verpflichtende Nutzung von emissionsarmer Ausbringungstechnik. Typische intensive Schweinemastbetriebe mit hohem Tierbesatz reduzieren ihre Nitrat- und Ammoniakverluste deutlich, insbesondere durch den Export von Wirtschaftsdünger, die Verschiebung der Wirtschaftsdüngerausbringung in das Frühjahr und die Nutzung von emissionsarmer Ausbringungstechnik. Extensivere Schweinemastbetriebe, die einen hohen Anteil des Schweinebestandes abbilden, verringern ihre Emissionen nur geringfügig. Typische Ackerbaubetriebe, die unter der DüV 2017 Wirtschaftsdünger importieren, sparen Kosten durch die Reduktion des Mineraldüngereinsatzes. Sie zeigen allerdings höhere Nitrat- und Ammoniakverluste, was die Gefahr von räumlichen Verlagerungseffekten aufgrund von Wirtschaftsdüngertransporten verdeutlicht. Der Transport kann jedoch eine Netto-Reduktion von allen untersuchten Umweltwirkungen realisieren. Der heterogene Effekt der DüV 2017 verdeutlicht die Notwendigkeit einer zielgerichteten Ausgestaltung von Vollzugsmechanismen und unterstützenden Maßnahmen für betroffene Betriebe. Darüber hinaus sollten Entscheidungsträger sensible Gebiete vor den negativen Auswirkungen von Wirtschaftsdüngerimporten schützen.

The Revision of the German Fertilization Ordinance in 2017: Analyzing Economic and Environmental Impacts at Farm-Level

Contents

List of Figures

List of Tables

Chapter 5

Chapter 6

Abbreviations

€	Euro
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
ct	Cent
DWD	German Meteorological Services
ECM	Energy-corrected milk
EF	Emission factor
eq	Equivalents
FADN	Farm Accountancy Data Network
FE	Freshwater eutrophication
FFD	Fossil fuel depletion
FO	Fertilization Ordinance
FSS	Farm Structure Survey
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LHS	Latin Hypercube sampling
LU	Livestock units
ME	Mean residual error
MFE	Mineral fertilizer equivalents
MINAS	Mineral accounting system
MR	Mean relative error
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NH_3	Ammonia

NO	Nitric oxide
NO_3^-	Nitrate
NO_x	Nitrogen oxides
NRW	North Rhine-Westphalia
P	Phosphorus
P_2O_5	Phosphate
PMF	Particulate matter formation
PO_4	Orthophosphate
Ref	Reference scenario
Ref N	Reference and replace nitrogen scenario
SCRs	Soil-climate regions
SO_2	Sulfur dioxide
TA	Terrestrial acidification
TAN	Total ammonia nitrogen
Trans	Transport scenarios
TransTech	Transport and improved technology scenario
VS	Volatile solids
WFD	Water Framework Directive

Chapter 1

Introduction

Nitrogen (N) and phosphorus (P) are essential nutrients for plant nutrition and indispensable for agricultural production. In ancient farm systems, N and P cycled between animal and crop production and N was mainly enriched by the symbiotic fixation from legumes. The fixation of atmospheric N with the Haber-Bosch process as well as the exploitation of P deposits enhanced the nutrient flows in farm systems and allowed disconnecting plant and animal husbandry. It increased agricultural production and facilitated the population rise in the twentieth century as illustrated by Erisman *et al.* (2008, p. 637). As farming activities take place in an open system, the loss of N and P to the environment is inevitable and a major environmental externality of agricultural production. N is emitted in different reactive forms with various impacts on nature and human. Nitrate (NO_3^-), mainly lost from agricultural soils following manure and chemical fertilizer application, poses a threat to ground and surface waters for drinking water use as high NO_3^- intake is linked to health damage (Townsend *et al.* 2003, pp. 242f.). Furthermore, NO_3^- leaching causes the eutrophication of limnic and coastal surface waters, leading among others to the loss of aquatic biodiversity and the formation of marine dead zones (Grizzetti *et al.* 2011, pp. 386ff.). Ammonia (NH_3), emitted to the air mainly from manure management, can lead after the deposition to a loss of biodiversity in terrestrial ecosystems (Dise *et al.* 2011, pp. 465ff.). Furthermore, NH_3 is a precursor of fine particulates which have a negative impact on human health (Townsend *et al.* 2003, pp. 241f.). During nitrification and denitrification processes in soils, N is emitted as the potent greenhouse gas nitrous oxide (N_2O) (IPCC 2006, p. 11.5) and contributing to climate change. P is mainly lost from agricultural soils via erosion and leads to the eutrophication of freshwater systems (Bennett *et al.* 2001, pp. 227ff.) as P is often limiting plant growth in these aquatic ecosystems (Sutton *et al.* 2013, p. 34). Moreover, P is a finite resource with uncertain projections on remaining reserves and of varying quality (Cordell & White 2011, pp. 2032ff.).

In Germany, several environmental targets exist to limit the negative environmental impact of N and P loss from agriculture. For the most part, national regulations are implementing EU directives as environmental policy is largely prescribed at EU level. Ground water bodies should not exceed the NO_3^- concentration of 50 mg l^{-1}, defined in the EU Nitrates Directive (European Council 1991). In Germany, this target value was missed in 18% of the representative ground water monitoring points in 2012 to 2014 and no decreasing trend is found (BMUB & BMEL 2016, pp. 46ff.). The EU Water Framework Directive (WFD) bundles efforts to protect fresh as well as coastal waters, aiming at “good status” regarding different ecological and chemical indicators (European Parliament, European Council 2000). Related

P and NO_3^- concentration targets, which are defined in national level, are for instance largely missed in streaming waters, at 63% and 81% of the monitoring points in 2016, respectively (UBA 2018c). However, P emissions stem not only from agriculture but also from waste water treatment. Environmental targets related to NH_3 emissions are not prescribed by concentrations but an emission budget. By 2030, Germany must have reduced its NH_3 emissions by 29% compared to 2005 (European Parliament; European Council 2016, p. 20), which corresponds to an allowed emission budget of 444 gigagram (gG) NH_3 a^{-1} (TI n.d.). The current emissions are 663 gG, stemming with 95% mainly from agricultural sources (UBA 2018b). In 2016, around 7% of the German greenhouse gas (GHG) emissions came from agriculture whereby N_2O from agricultural soils plays a major role (UBA 2018a, pp. 71, 445). Binding GHG reductions targets do not exist for agriculture, but its contribution to reach existing cross-sectoral reduction targets are frequently discussed (BMUB 2014, pp. 59ff.).

1.1 Motivation

In Germany, the Fertilization Ordinance (FO) (BMEL 2017a) is the central instrument to limit the emission of N and P from agriculture and, therefore, to reach several described environmental targets. It comprises numerous measures which regulate the management of chemical and manure nutrients in farming systems. The FO implements the Nitrates Directive countrywide in Germany and is central to reach targets laid down in the WFD. It also includes measures on the storage and application of manure which limit NH_3 emissions and contribute an important emission reduction to meet the budget under the EU Directive on the Reduction of National Emissions of Certain Atmospheric Pollutants (European Parliament; European Council 2016). The FO was revised in June 2017, triggered by infringement proceedings by the EU Commission. The Commission complained about shortcomings in reaching, amongst others, target concentrations in ground and coastal waters and about the German government not taking adequate action to tackle the problem (EC 2014).

The legislative process ended with a revised FO, which comprises numerous new and tightened measures regarding nutrient application thresholds, technology allowances, management prescription, and enforcement. The FO 2017 is most likely linked to costs for farmers to comply. These costs are caused for instance by the obligatory use of costly low-emission manure application techniques, required investments into additional manure storage and management changes to meet stricter nutrient application thresholds. A detailed estimation of these costs is still missing. First quantifications at aggregated scale, partly provided within the legislative process, hint at relevant cost burden for the agricultural sector (Karl & Noleppa 2017, pp. 10ff.; BMEL 2017b, pp. 70ff.). However, past research on costs induced by agri-environmental policy indicate the need to take farm heterogeneity into account (e.g. Mack & Huber 2017) as the compliance costs largely differ depending on farm characteristics. Knowledge on the costs is essential for discussions on the financial burden for the agricultural sector induced by environmental policies, the design of complementary measures and upcoming revisions of the FO.

Besides the cost perspective, the change of emissions induced by the revised FO is of importance to assess its effectiveness and to quantify the contribution to reach the described environmental targets. The legislative process comprised qualitative estimates (BMEL 2016, pp. 53ff.), but there is a lack of detailed quantitative studies. As the FO consists of numerous and interacting measures, which target different N species and P, the actual emission change is complex to quantify. Furthermore, the change is most likely also determined by farmers' adaption to the changed regulation as well as by specific soil-climate conditions. To capture the unintended consequences of the FO revision, the assessment of environmental impacts also needs to address potential pollution swapping between different regions and emissions. Reactive N losses prevented at one spot of the so-called N flow may lead to an increase of emissions at the following spots (Oenema & Velthof 2007, p. 31).

The dissertation at hand assesses the economic and environmental impacts of the revised FO. The work largely results from an interdisciplinary research project on the farming sector in the German federal state of North Rhine-Westphalia (NRW), which was funded by the Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia. The relevance of the FO differs depending on the structure of agricultural production and the regional environmental status. NRW is part of Northwest Germany, which is characterized by regionally concentrated intensive livestock production and high regional nutrient surpluses (LWK NRW 2018, pp. 24, 57ff.; LWK Nds. 2017, pp. 26ff.). Farms in these regions will most likely need to adapt to the stricter nutrient application thresholds of the FO 2017. To comply with the outdated thresholds of the FO 2007, already a great amount of manure was transported between regions with high and low stocking density (LWK NRW 2014, pp. 118ff.; LWK Nds. 2016, pp. 142ff.). This exchange will most likely increase under the FO 2017. In contrast, especially in low mountain ranges small-scale and more extensive farming exists and is often linked to outdated technology. Hence, such farms may face the need for adjustment due to changed technology allowances of the FO. Ground and surface waters in NRW largely exceed the target concentrations. 16% of the monitoring points for ground water exceeded the threshold of 50 mg NO_3^- l^{-1} in 2017 (MULNV 2018), whereby the share of groundwater bodies categorized as NO_3^- loaded is higher (ELWAS-WEB 2019). From 2005 to 2016, no relevant reduction is found at monitoring points under arable land (LWK NRW 2018, p. 73). Surface waters in NRW did partly not meet the targeted environmental status between 2012 and 2014, 34% due to P, 19% due to nitrite, 17% due to ammonium and 2% due to NO_3^-. Modelling results suggest that approximately 72% of N and 48% of P emissions into surface waters come from agriculture (LWK NRW 2018, p. 74f.).

Hence, assessing the environmental and economic impact of the revised FO in NRW is of particular interest as farms in the federal state may be strongly affected by the FO 2017 and as there is a need to improve the environmental status of ground and surface water bodies.

1.2 Research Aims

The overall research aim of this dissertation is the assessment of the environmental and economic impact of the FO 2017 at farm-level. Thereby, the methodological focus is on the application and extension of the bio-economic single farm optimization model FarmDyn (Britz *et al.* 2018). FarmDyn has been initially developed to assess marginal abatement costs on dairy farms (Lengers et al. 2014). In a further application, independent of the main model development, the model is used to assess the investment behaviour and income of livestock farms under single water protection policies (Budde 2013). Furthermore, FarmDyn represents a variety of farming activities, also allowing the assessment of biogas production under different support schemes (Schäfer et al. 2017). The use of bio-economic models such as FarmDyn for the assessment of agri-environmental policies has numerous advantages. Firstly, they allow a detailed representation of farming activities and related environmental externalities. This is of importance if the assessed policy measures are directly linked to management decisions such as the fertilizer use and if the assessment also includes the quantification of on-farm emissions. Thereby, FarmDyn is able to represent on-farm nutrient flows and link economic and environmental impacts to different steps of this flow in the farming system. Secondly, farm models allow taking farm heterogeneity into account (Blanco 2016, p. 2), which is needed for a comprehensive assessment of agri-environmental policies (e.g. Mack & Huber 2017). Thirdly, farm modelling is a useful tool for ex-ante policy assessment when the policy impact cannot yet be directly observed (Janssen & van Ittersum 2007, p. 623). The revised FO came already in force in June 2017. However, numerous measures of the FO will fade in within the next decade and certain environmental impacts, such as changes in NO_3^- leaching, appear in the medium and long run. Therefore, the study is understood as an ex-ante assessment.

The use of single farm models comprises the decision which farms to model. Therefore, the first research aim targets the selection of farms and the provision of needed data to assess the revision of the FO:

(1) Developing a data-driven farm typology for the German federal state of NRW to assess agri-environmental policies.

This typology allows selecting farm types which are most representative regarding farm numbers, land or livestock covered. Furthermore, when selecting farm types which are most affected by the policy change, their importance in the farm population can be quantified. The typology is restricted to NRW due to the regional focus of the described research project and the particular importance of the FO in this federal state. The single farm model FarmDyn is applied to selected farm types from the developed typology to address the following research aim:

(2) Assessing the economic and environmental impact of the revised FO on selected farm types using a coupled crop and farm model.

The coupling of a crop modelling framework to the single farm model FarmDyn allows the detailed representation of cropping activities. It covers the relation between fertilizer use and yield, the precise quantification of NO_3^- leaching at field level, and the inclusion of different soil-climate conditions in NRW. The model coupling is the core methodological development of the described interdisciplinary research project and requires the integration of agricultural economics and plant science. However, the coupled models can only be applied to a small number of farms as the computing time is very high. Therefore, the most representative and affected farm are selected from the derived farm typology. Besides the use of results from a crop modelling framework, cropping activities can be characterized by fixed and simplified relations between fertilizer use and yield response. Such a representation of cropping activities in FarmDyn is used to address the following research aim:

(3) Estimating the distribution and drivers of compliance costs with the revised FO in a farm population under limited data availability.

Thereby, the focus is on the economic impact of the FO, quantified as the on-farm costs to comply with the regulation. The model is applied to all farms of a population instead of selected farm types from a typology, as in relation to the second research aim. The use of the simple representation of cropping activities keeps computing time low and facilitates to run FarmDyn for the needed large number of farms. Single farm data from official German statistics are used as the solely comprehensive and accessible source for information on the whole farm population. Due to data privacy requirements, however, these data cannot be directly provided for the model initialization and parametrization. Therefore, a sampling approach is applied based on the distribution of observed farm characteristics to create a representative farm population for the modelling exercise.

The single farm model comprises prominent compliance strategies of farms to fulfill the requirements of the FO. Thereby, the export of excess manure is a central measure for livestock farms to adapt to nutrient application thresholds. Already under the FO 2007, large amounts of manure were transported in Northwest Germany (LWK NRW 2014, pp. 118ff.; LWK Nds. 2016, pp. 142ff.). In the applied farm model, nutrient flows and environmental impacts are only quantified within the system boundaries of the farm gate. Manure transport, however, is linked to additional emissions for the transport itself and potentially on the manure importing farm. The integrated assessment of manure transport beyond farm gate boundaries is addressed in the following research aim.

(4) Quantifying the environmental impact of manure transport induced by the FO using a life cycle approach.

Compared to the assessment of the FO with a bio-economic farm model, the applied methodology of a life cycle assessment (LCA) does not include economic reasoning. Emissions along the life of manure from excretion to application on the field are quantified for different management strategies in relation to the FO. More specifically, scenarios with and without manure transport are compared. In contrast to the other research aims, the life cycle approach is not part of the described research project.

1.3 Proceedings

The dissertation is structured as followed. Chapter 2 summarizes the most important measures of the FO 2007 and 2017. The methodology to develop the farm typology for NRW as well as exemplary farm types are presented in Chapter 3. Chapter 4 comprises the assessment of the economic and environmental impact of the FO with the coupled crop and farm models for farm types selected from the typology. In this context, the single farm model FarmDyn as well as the concept of the model connection is introduced. Chapter 5 focuses on the distribution and the drivers of compliance costs in the population of specialized dairy and pig fattening farms in NRW. The LCA of manure transport under the FO is found in Chapter 6. Finally, Chapter 7 concludes.

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Chapter 2

The revision of the German Fertilization Ordinance in 2017[1]

Abstract

The Nitrates Directive is the core legislation to reduce nitrate emissions from agriculture to water bodies in the EU. In Germany, the directive is mainly implemented by the national Fertilization Ordinance (FO) which aims, besides nitrate, at ammonia and phosphate losses. The FO has been currently revised as a reaction to infringement proceedings against Germany by the European Commission. The revision includes considerable changes, among others: a compulsory and clearly specified fertilizing planning, the inclusion of biogas digestate from plant origin in the organic nitrogen application threshold, a new methodology to calculate an obligatory nitrogen and phosphate balance, a reduction of legal nutrient balance surpluses, stricter banning periods for fertilizer application in autumn, a stepwise introduction of reduced ammonia emission application techniques and the possibility to introduce additional measures in pollution hot spots. Research on the environmental and economic impact of the revision is still rare. This chapter contributes a summary of the most relevant changes by opposing the FO from 2007 and 2017. A detailed scientific analysis on the revised FO is necessary to clarify the economic impact on farms and the contribution to reaching existing environmental targets.

[1] This chapter is published in a previous version as the following article: Kuhn, T. 2017. The revision of the German Fertiliser Ordinance in 2017, Institute for Food and Resource Economics, Discussion Paper 2017:2, http://www.ilr.uni-bonn.de/agpo/publ/dispap/download/dispap17_02.pdf (accessed 27.03.19). The research is funded by the Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (MULNV) within the framework of the teaching and research focus "Umweltverträgliche und Standortgerechte Landwirtschaft" (USL).

2.1 Introduction

The loss of nitrogen (N) and phosphorus (P) from farming systems to the environment poses a threat to groundwater and surface water quality, biodiversity, and climate (Sutton *et al.* 2013, pp. 32ff.). In Germany, the Fertilization Ordinance (FO) (BMEL 2017a) is the key command and control measure to limit N and P emission from agriculture. The FO mainly implements the EU Nitrates Directive in Germany which aims at reducing and preventing nitrate (NO_3^-) emissions from agriculture to water bodies (European Council 1991). NO_3^- concentration in groundwater should be below 50 mg l^{-1}, which is also the threshold for the NO_3^- concentration in drinking water to protect human health from possible harm, as laid down in the EU Drinking Water Directive (European Council 1998). Furthermore, NO_3^- emissions to surface waters cause the eutrophication of limnic and marine ecosystems. Related environmental targets are, amongst others, defined in the EU Water Framework Directive (WFD) (European Parliament, European Council 2000) and the EU Marine Strategy Framework Directive (European Parliament; European Council 2008) (Figure 2.1).

To fulfil the requirements of the Nitrates Directive, member states have to identify so-called "vulnerable zones", develop national action programs to tackle NO_3^- emission and report in defined periods about the development of NO_3^- pollution to the European Commission. The Nitrates Directive partly specifies precise measures, as for instance the application limit for organic N of 170 kg ha^{-1}, but member states have a considerable freedom in the design of their action program. The FO as the German implementation was revised in spring 2017 (BMEL 2017a), triggered by infringement proceedings against Germany. The European Commission criticized, among others, that the NO_3^- concertation in groundwater bodies and coastal waters has stopped to reduce and partly increased over the last reporting periods and that Germany did not take adequate action (EC 2014). The revision process, which started in 2011, was completed by the revised FO passing the German Federal assembly in spring 2017. In this context, also the fertilizing law was amended as the introduction of certain measures in the FO required an update of the legal basis.

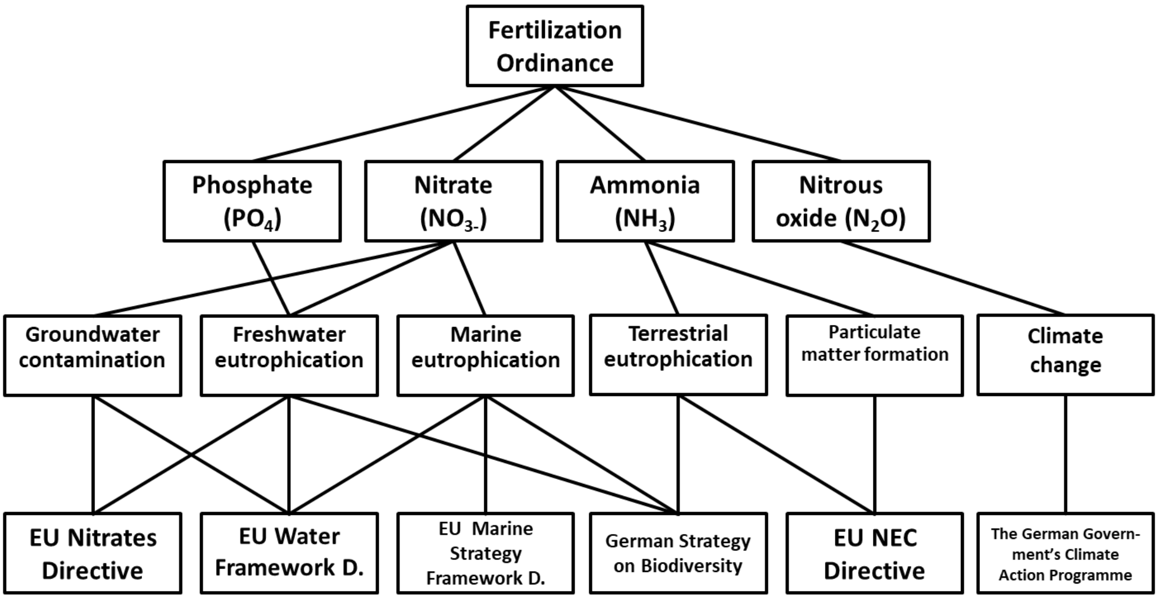

Figure 2.1 Simplified overview on emissions, environmental impacts and relevant national and European regulations related to the Fertilization Ordinance

Source: own illustration; D. - directive

Albeit focusing on NO_3^-, the FO impacts on nitrous oxide (N_2O), ammonia (NH_3) and P emissions. Because of the inclusion of measures to lower P and NH_3 losses, the FO is crucial to meet environmental targets for freshwater eutrophication (FE) as laid down in the WFD, or the prescribed national NH_3 threshold defined in the EU Directive on the Reduction of National Emissions of Certain Atmospheric Pollutants (European Parliament; European Council 2016). Measures of the FO indirectly impact on N_2O emissions from farming systems. This is mainly caused by the fact that the reduction of total N input, as induced by the FO, can lower all emissions along the N loss pathway (Oenema & Velthof 2007, pp. 31f.). Furthermore, NO_3^- and NH_3 losses are indirect sources of N_2O emissions. Therefore, the revised FO is designated to realize the major share of the greenhouse gas (GHG) reduction requirements from the agricultural sector in Germany (BMUB 2014, pp. 59ff.).

The aim of this chapter is to provide a summary of the changes in the FO and a discussion of possible impacts. Furthermore, the scientific literature on the revision is summarized. The provided information is important for future research on the economic and environmental impact of the revision. In addition, knowledge of national policies tackling nutrient loss from agriculture is from special interest for an international audience as similar policies are applied and frequently revised in numerous countries.

2.2 Measures of the Fertilization Ordinance

The FO consists of a bunch of measures which are partly interlinked. Generally, one can differ between measures that limit the quantity of applied nutrients (application threshold, nutrient balance) and detailed technical or management specifications (e.g. application techniques). The first are ‘goal oriented regulations’, leaving farmers different abatement options to comply, whereas the latter are ‘means-oriented regulation’, which define a precise measure to adapt following the terminology of Schröder & Neeteson (2008, pp. 418f.). Furthermore, the FO specifies the sanctions for violations. There are hints of a lack of enforcement regarding fertilizer regulations in Germany (LWK NRW 2014, pp. 53ff.), however, reliable and representative data is missing. As measures of the FO are partly relevant for the cross compliance of payments under pillar one of the EU Common Agricultural Policy, violations are sanctioned by cutting the direct payment. Furthermore, the FO defines which violations are qualified as an administrative offense under national law and are linked to monetary fines. This section explains the most important elements of the FO and the differences between FO 2007 (BMELV 2007) and FO 2017 (BMEL 2017a) which Table 2.1 summarizes. The enforcement of the respective measure is reported in the corresponding section.

Table 2.1 Most important measures of the Fertilization Ordinance 2007 and 2017

Measure	Fertilization Ordinance 2007	Fertilization Ordinance 2017
Fertilizing planning	Unspecified and not binding fertilizing planning	Clearly defined and compulsory fertilizing planning
Organic N application - threshold	170 kg N $ha^{-1}a^{-1}$	170 kg N $ha^{-1}a^{-1}$
Organic N application – calculation	Only N from animal manure	N from animal and plant sources (biogas digestate from plant origin)
Organic N application – derogation	Up to 230 kg $ha^{-1}a^{-1}$ for grassland when meeting certain requirements.	Planned, design not known.
Nutrient balance – allowed surplus	60 kg N $ha^{-1}a^{-1}$ 20 kg P_2O_5 $ha^{-1}a^{-1}$	50 kg N $ha^{-1}a^{-1}$ 10 kg P_2O_5 $ha^{-1}a^{-1}$; 0 kg P_2O_5 $ha^{-1}a^{-1}$ on highly P enriched soils
Nutrient balance – calculation scheme	Surface balance approach	Surface balance approach, quantification of on-farm forage yields via animal nutrient need; stepwise introduction of farm gate balance approach[1]
Banning periods – fixed	Grassland 15.11-31.1 Arable land 1.11-31.1	Grassland 1.11-31.1 Arable land 1.10-31.1
Banning periods – after harvest of the main crop	Organic nutrient application restricted to 40 kg ammonia N or 80 kg total N for catch crops, winter crops, and straw rotting	Total nutrient application restricted to 30 kg ammonia N and 60 kg total N for catch crops, winter rapeseed, field forage and winter barley following cereals in crop rotation
Reduced ammonia emiss-ion application techniques	Broadcast spreader allowed	Broadcast spreader banned except on bare land followed by incorporation; compulsory from 2020 onwards on arable, 2025 on grassland
Minimum manure storage capacity	6 month[2]	6 months, 9 months for farms >3 livestock units ha^{-1}
Minimum distance from surface water for fertilizer application	3 meter 1 meter (if working widths equals spreading widths or if boundary spreading devices are used) 3 meter (steeply sloping ground)	4 meter 1 meter (if working widths equals spreading widths or if boundary spreading devices are used) 5 meter (steeply sloping ground)
Additional measures in pollution hot spots (nitrate in ground- and phosphate in surface waters)	-	The Federal States have to apply at least three out of 14 predefined measures in pollution hotspots; more measures optional

Source: own illustration based on BMELV 2007 and BMEL 2017a; [1] the introduction of the farm gate balance is subject to a separate directive to come; [2] defined in Federal law on requirements for manure storage facilities; N - nitrogen; P_2O_5 - phosphate; P - phosphorus

2.2.1 Fertilizing planning

The German action program has never included total application limits for chemical fertilizer and manure as for instance the implementation of the Nitrates Directive in the Netherlands or

Denmark (Schröder & Neeteson 2008, pp. 420ff.; Kronvang *et al.* 2008, pp. 146f.). In the FO 2007, it is laid down that nutrient application should generally meet plant need and fertilizing planning has to be done. However, clear specifications on the methodology as well as sanctions for non-compliance are missing. To fill this gap, the FO 2017 introduces a compulsory and clearly defined fertilizing planning.

Table 2.2 Exemplary fertilizing planning for nitrogen according to the Fertilization Ordinance 2017

Factors of fertilizer need estimation	
Crop	winter wheat
N need [kg N ha^{-1}]	230
Yield level default [t ha^{-1}]	8
Three-year average yield [t ha^{-1}]	9
Yield difference [t ha^{-1}]	1
Correction factors (N delivery, yield differences)	
Mineral N in spring [kg N ha^{-1}]	- 40
Change based on yield difference [kg N ha^{-1}]	+ 10
N from soil pool at humus-rich plots [kg N ha^{-1}]	- 20
N from organic N applied in year before [kg N ha^{-1}]	- 18
N from previous crop [kg N ha^{-1}]	0
N need	162
Corresponding fertilizer application	
N organic applied [kg N ha^{-1}]	60
N organic accounted [kg N ha^{-1}]	36
N chemical applied [kg N ha^{-1}]	126

Source: own calculation based on BMEL (2017a, pp. 22f.); winter wheat after silage maize, yield level of 9 t ha^{-1}a^{-1}, use of 10 m^3 pig manure to winter wheat and 30 m^3 to the previous crop (6 kg N m^{-3} manure); N - nitrogen

In the FO 2017, the obligatory fertilizing planning is restricted to N and P. N needs for different crops and allowed correction related to the yield level is defined by the directive. The yield level, at which farmers are allowed to aim, results from the average yield of the last three years. The allowed chemical fertilizer application is determined by taking N delivery from the soil and a prescribed share of N from manure into account. Farmers can either measure the nutrient content of manure or use the default value. Table 2.2 exemplarily shows the fertilizing planning for winter wheat following silage maize with the use of manure. The fertilizing planning for P_2O_5 is not further specified by the FO 2017, but application must relate to expected yields and P_2O_5 in soil, obtained from obligatory soil testing. The violation of the requirements of the fertilizing planning is sanctioned as an administrative offense. It is only allowed to correct the calculated limit if higher plant need occurs due to factors like weather conditions.

A central element of the fertilizing planning is the accounting of N from organic sources, including animal manure and biogas digestates. The compulsory accounting in the first year is between 3% and 90%, depending on the manure type. 10% of organic N has to be accounted in the year after application. Furthermore, delivery from soil, which has been fertilized with manure over longer periods, and N delivery from the soil in spring is included. The utilization of organic nutrients is often measured as Mineral fertilizer equivalents (MFE). Generally, MFE are the amount of chemical fertilizer which can be replaced with manure (Gutser *et al.* 2005, pp. 440ff.). Table 2.3 summarizes the default MFE values of the most important manure types from the FO 2017. The MFE relate to the manure N content measured after storage or calculated based on the default animal excretion minus stable and storage losses (Section 2.2.2). Hence, the MFE only partly represents the farm N efficiency. When applying the default stable and storage loss factors and the described MFE from the FO, around 50% to 60% of the excreted N from pig and cattle manure is accounted for plant nutrition (Klages *et al.* 2017, p. 56). However, the values in Table 2.3 only represent the short term MFE. As other N sources, e.g. soil from N on humus rich plots, also need to be taken into account in the fertilizing planning, the FO 2017 includes slightly higher long-term MFE.

Table 2.3 Mineral fertilizer equivalents in the Fertilization Ordinance 2017

Manure type	First-year MFE	Second-year MFE
Cattle manure	50%	60%
Pig manure	60%	70%
Pig and cattle liquid manure	90%	100%
Solid manure	25%	35%
Pig solid manure	30%	40%
Dry chicken faeces	60%	70%
Liquid biogas digestate	50%	60%
Solid biogas digestate	30%	40%

Source: BMEL (2017a, pp. 5, 22); MFE - mineral fertilizer equivalents; related to total N

2.2.2 Organic nitrogen application threshold

The Nitrates Directive directly limits the application of manure N to 170 kg ha^{-1}. The N use efficiency decreases with higher shares of organic N and the danger of NO_3^- leaching rises (Osterburg & Techen 2012, p. 51; Gutser *et al.* 2010, pp. 36ff.). Both, FO 2007 and 2017, include this threshold. It is calculated from animal excretion minus default values for NH_3 volatilization and has to be met on farm-level and not on single plots.

Under the FO 2017, the threshold of 170 kg N ha^{-1} persists, but more nutrient sources are included and default loss factors change. First, biogas digestates from plant origin are now taken into account. In Germany, biogas production expanded strongly until 2014 (FNR 2015) with maize silage beeing the major feedstock (DBFZ 2013, p. 55). The use of crops as feedstock leads to an additional production of organic nutrients as digestates. Second, the default values for N losses from stable and application are lowered, e.g. for pig manure from 30% to 20%. For pasture grazing, default loss factors are reduced from 75% to 30%. The reduction of the default loss factors has the same effect as lowering the allowed N application threshold.

Under the Nitrates Directive, member countries can apply at the European Commission for the derogation from the organic N threshold, meaning that under certain conditions higher manure application rates are allowed. In the past, the application up to 230 kg N ha^{-1} was legal for intensive grassland but this exception was linked to requirements like low nutrient balances or the use of certain manure application techniques. The derogation is primarily relevant for intensive dairy farms in Northwest and South Germany. Overall, around 1,100 farms (32,000 ha) applied it in 2011 (Osterburg & Techen 2012, p. 218). It is planned to request for derogation at the European Commission, as stated in the FO 2017, but detailed terms and linked requirements are not known yet.

2.2.3 Nutrient balance

The German action programs have always included nutrient balances as an indicator for potential nutrient losses to the environment. Farmers have to calculate an annual, historical nutrient balance and the surplus of the balance is restricted. In the current revision, the methodology, as well as the allowed surpluses and the sanctions, are adapted.

Calculation methodology

Under the FO 2007 and 2017, the nutrient balance is calculated as a surface balance (Figure 2.2). N and P_2O_5 input via manure and chemical fertilizer is opposed to the nutrient removal with the harvested product. The difference should not exceed a certain threshold in a sliding multi-year average. There are two general approaches available to obtain the balance: the calculation of surpluses related to certain plots and the aggregation to farm-level or the calculation at farm-level. Nutrient input via manure is calculated based on animal excretion. NH_3 losses from the stable and application are subtracted. The FO specifies default values for animal excretion and standard loss factors. The nutrient removal is derived from the content of harvested products which is also defined by the FO. Under both FO, only when exceeding a certain farm size and intensity characteristics, farms are obliged to calculate the nutrient balance. In the FO 2007, values for P_2O_5 removal with the harvested product have been missing and were specified by institutions on the federal level.

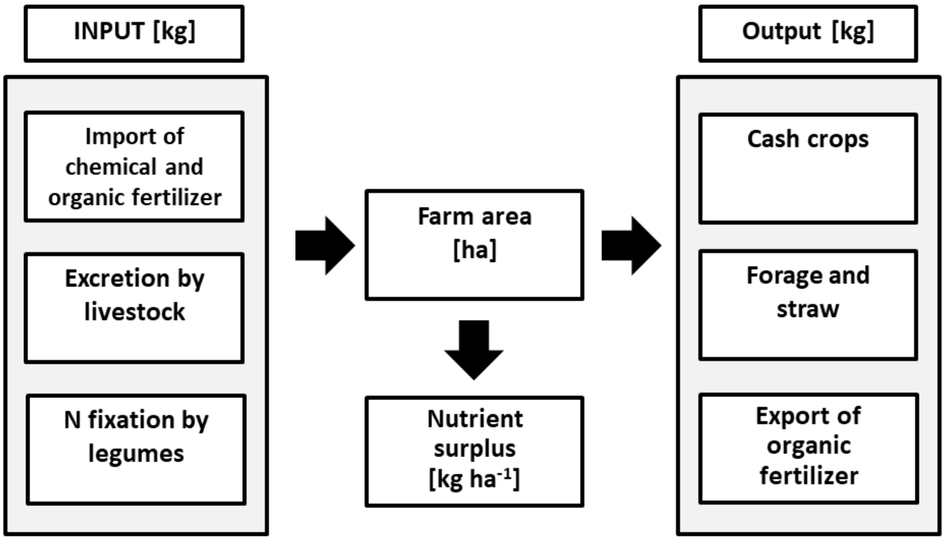

Figure 2.2 Overview on the soil surface balance

Source: own illustration based on VDLUFA (2007, p. 7) and Kolbe & Köhler (2008, p. 40)

The main methodological changes under the FO 2017 are for livestock farms growing a large share of forage on the farm, hence, especially dairy and beef production. Under the FO 2007, the validity of nutrient balances from these farm types is very limited as the nutrient removal with the harvested fodder is often overestimated (Osterburg & Techen 2012, pp. 190f.). Under the FO 2017, nutrient removal via forage production is not specified by the yield but estimated based on the feed need of the present animal stock. This leads to a cross validation of the nutrient removal from forage harvest and animal nutrient need.

Allowed surplus

The restriction of the allowed surplus links the calculation of the nutrient balance to reduction efforts and the limitation of nutrient losses. The relevant surplus relates to the total farm and not to single plots. Under the FO 2017, the allowed N surplus, calculated as a three-year sliding average, is lowered from 60 to 50 kg N ha^{-1} from 2020 onwards. This means that surpluses from the year 2018 and the following are relevant. The allowed P_2O_5 surplus, calculated as a six-year sliding average, is lowered from 20 to 10 kg P_2O_5 ha^{-1} from 2023 onwards.

On P-enriched soils, no surplus is allowed. The P status of soils is determined by compulsory soil sampling. For clarification, the FO specifies thresholds of P soil content that are qualified as P-enriched. This surplus restriction is regulated in the fertilizing planning to ensure that the inputs are reduced on the actually affected plots (Section 2.2.1). Institutions on the federal level can further limit P_2O_5 fertilizing in single cases if damage of water bodies due to P_2O_5 fertilizing is present.

Furthermore, the FO 2017 includes sanctions for not complying with the prescribed nutrient surpluses which are missing under the FO 2007. Exceeding the allowed surpluses is qualified as an administrative offense and leads to a compulsory consultation on the fertilizer practice.

Farm gate balance approach

In the revision process, policymakers agreed on the stepwise introduction of a balance following the farm gate approach. A farm gate balance, in contrast to a surface balance, opposes nutrient input via purchased feed, animals and fertilizer to nutrient output via sold products. It is seen as a more transparent and valid methodology as more parameters can be approved by farm accounting data (SRU 2015, pp. 324ff.). The new balance is not part of the FO, but is defined in a separate directive. The revision of the fertilizing law created the legal basis to capture the parameters which are needed for the farm gate approach and includes the following specifications: From 2018 onwards, farms need to follow the farm gate balance if they have a higher stocking density than 2.5 livestock units (LU) ha^{-1} and more than 50 LU in total or more than 30 ha agricultural land. Furthermore, farms which import manure from other farms are included. From 2023 onwards, all farms above a certain size are obliged to estimate nutrient surpluses according to the farm gate balance approach (BMEL 2017b, p. 7). A group of experts appointed by the Federal Ministry of Food and Agriculture has issued recommendations on the Directive (Klages *et al.* 2017).

2.2.4 Banning periods and manure storage capacities

The application of N fertilizer, especially manure, in autumn and winter is particularly linked to the risk of NO_3^- leaching (Di & Cameron 2002, p. 241; Cameron *et al.* 2013, p. 151). Therefore, the FO 2007 and 2017 restrict fertilizer application after the harvest of the main crop and forbid the N fertilizer application in a defined period. This measure only aims at fertilizers containing N but P_2O_5 is affected likewise as both nutrients are combined in manure. With regard to manure, this measure is linked to the maximum manure storage capacity that farms have to prove as livestock excretion during the banning period must be stored.

Table 2.4 Banning periods under Fertilization Ordinance 2007 and 2017

	Fertilization Ordinance 2007	Fertilization Ordinance 2017
Banning periods – fixed	Grassland 15.11-31.1 Arable land 1.11-31.1	Grassland 1.11-31.1 Arable land 1.10-31.1
Banning periods – after the harvest of the main crop	Organic nutrient application restricted to 40 kg ammonia N or 80 kg total N for catch crops, winter crops and straw rotting	Total nutrient application restricted to 30 kg ammonia N and 60 kg total N for catch crops, winter rapeseed, field forage and winter barley following cereals in crop rotation

Source: own illustration based on BMELV 2007 (p. 5) and BMEL 2017a (pp. 8f.)

Under the FO 2017, banning periods for manure application are prolonged on arable and grassland and the application after the harvest of the main crop is more restricted (see Table 2.4 for details). Moreover, they apply for N from organic and chemical sources. Under the FO 2007, the use of chemical fertilizer after the harvest of the main crop and before the fixed banning period was not restricted. Generally, the changes lead to a stronger limitation of manure application in autumn. Banning periods may be postponed by two weeks on a regional level, but the total time of the banning period is not allowed to change. It has to be noted that there are already regulations present in some federal states which limit the manure application after the harvest of the main crop.

In the FO 2007, the minimum storage capacity is not specified because it is defined in the Federal law on the requirements for manure storage facilities. Minimum storage capacity is generally six months. In the 2017 revision, the minimum storage capacity is included in the FO. Generally, the capacity must correspond to the period when a farm is not able to apply manure. The defined minimum storage capacity remains the manure production of six months and applies for animal manure and digestates from biogas production. For farms with more than 3 LU ha^{-1} or without own farm land, 9 months must be available from 2020 onwards. Farms do not have to provide storage capacity directly, but can prove it via contracts with third parties.

2.2.5 Manure application techniques and manure incorporation

The application of manure is a major source of NH_3 emissions (Rösemann *et al.* 2015, pp. 12f.), whereby the used application techniques and management highly impact on the amount of volatilization (Webb *et al.* 2010, pp. 40f.). Under the FO 2017, broadcast spreaders are banned for the application in crops. Only techniques ensuring the application in stripes or directly in the soil, as for instance trailing shoe or injection, are permitted. They become compulsory on arable land in 2020 and on grassland in 2025. On bare land, broadcast spreading is still allowed. If liquid manure is applied on bare land, farmers have to incorporate it within four hours. Under the FO 2007, the time to incorporate manure was not clearly specified.

2.2.6 Further measures

Solid manure and compost

Under the FO 2007, there are no banning periods and required minimum storage capacity for solid manure and compost. Manure and compost are characterized by a low share of mineral N and a wide carbon:N relation, which makes only small shares of N quickly plant available (Gutser *et al.* 2005, pp. 441ff.). This implies a low risk of NO_3^- leaching during autumn and winter. Under the FO 2017, solid manure and compost application are forbidden from December 15th to January 1st and a minimum storage capacity of solid manure of two months is required from 2020 onwards Furthermore, compost is included in the organic N application threshold but it has to be met in a three-year average which allows application up to 510 kg N ha^{-1} in a single year.

Vegetable and fruit production

Vegetable production is often characterized by low N efficiency as, amongst others, certain crops require high N input or are characterized by high residual N after harvest (Cameron *et al.* 2013, pp. 155f.). Under the FO 2007, the additional nutrient surpluses were allowed for certain crops like broccoli or leek. This resulted in a legal surplus of up to 220 kg N ha^{-1}. Under the FO 2017, additional N surpluses for vegetable production are generally limited to 60 kg ha^{-1}. In addition, the compulsory fertilizing planning is also specified for vegetables. Banning periods for vegetables and certain berries differ from general requirements by lasting only from December 1st to January 1st.

Fertilizer application: soil status, minimum distance, and prevention of runoff

The FO includes specifications on the allowance of fertilizer application depending on the soil status (e.g. frozen soil), the minimum distance to surface water and the prevention of fertilizer run off. Under the FO 2017, the fertilizer application depending on soil status is specified and the minimum distance to surface water for fertilizer application is slightly increased (Table 2.1). Furthermore, the prevention of fertilizer runoff is generalized under the FO 2017 and non-compliance is sanctioned as an administrative offense.

Data reporting and integration

Under the FO 2017, federal states can prescribe that farmers submit their nutrient balance to the institutions being in charge of the FO enforcement. Based on a combination of national and federal law, manure flows between farms are already accounted in some federal states. Combining the information on exported and imported nutrients, nutrient balances and farm-specific data used for the direct payment calculation allows detecting possible violations easier than before. Moreover, federal states can decree that the nutrient need and application under the fertilizing planning is aggregated to single values for the whole farm, which facilitates the enforcement.

2.2.7 Regional differentiation of measures

Under the Nitrates Directive, member states can choose to implement the national action programs either in identified so-called vulnerable zones or on the whole territory. In Germany, measures of the FO 2007 and 2017 are compulsory nationwide. However, the FO 2017 includes a new element which allows and prescribes federal states to adopt measures in defined areas.

First, the FO 2017 includes a bunch of additional measures for tackling emissions in pollution hotspots (Table 2.5). Relevant regions are defined depending on the NO_3^- concentration and trend in groundwater bodies and the eutrophication of surface water, especially related to the P concentration. Concentration thresholds are related to the environmental targets of the Nitrates Directive and the WFD. In these pollution hotspots, federal states have to apply at least three additional measures. They can choose which measures to apply and are allowed to prescribe more than three measures. It has to be noted that the measures are not compulsory for farms which prove to have an N surplus below 35 kg ha^{-1} (Section 2.2.3).

Table 2.5 Comparison of general measures and additional measures for pollution hotspots

Measure	General	Optional in pollution hot spots
Correction of fertilizer need in fertilizing planning	Not limited	Restricted to 10% of the originally estimated fertilizer need
Testing of nutrient content of manure and biogas digestate before application	Optional	Compulsory
Further restriction of P_2O_5 fertilizer application	Only in singular cases possible	In the defined area possible
Testing of N delivery from soil	Optional	Compulsory
Minimum distance to surface water for fertilizer application	4 meter 1 meter (if working widths equals spreading widths or if boundary spreading devices are used) 5 meter (steeply sloping ground)	5 meter 1 meter (if working widths equals spreading widths or if boundary spreading devices are used) 10 meter (steeply sloping ground)
Incorporation of manure on bare land	As fast as possible, at least in four hours	As fast as possible, at least in one hour
Banning periods for P fertilizer	Not included	15.11 to 31.1, prolongation of up to 4 weeks possible
Banning periods for N fertilizer on grassland	1.11 to 31.1	15.10 to 31.1
Banning periods for solid manure	15.12 to 15.1	15.11 to 31.1, prolongation of up to 4 weeks possible
Banning periods for N application to certain fruits and vegetables	1.12 to 31.1	1.11 to 31.1
Obligation to calculate nutrient balance[1]	Farms characterized by >15 ha, >750 kg organic N or import of manure or biogas digestate	Farms characterized by >10 ha, >500 kg organic N or import of manure or biogas digestate
N surplus limitation	50 kg N $ha^{-1}a^{-1}$	40 kg N $ha^{-1}a^{-1}$
Minimum storage capacity for liquid manure	6 months	7 months
Minimum storage capacity for solid manure	2 months	4 months

Source: own illustration based on BMEL 2017a; [1] there are further exceptions for specialized farms which are not described here; N - nitrogen; P_2O_5 - phosphate; P - phosphorus

Second, the federal states are allowed to lower requirements outside of pollution hotspots. This includes lowering the minimum storage capacity for grassland based farms with high stocking density from nine to six months and excluding more farms from the obligation to calculate nutrient balances. The latter can be expanded to farms which have less than 30 ha, less animal manure production than 110 kg N ha^{-1} and do not import manure or biogas digestate.

2.3 Studies on the impact of the revision

There is little research on the impact of the revised FO in Germany. This is partly caused by the fact that the FO 2017 was just recently amended and detailed design of measures was unclear until the end of the revision process. Hence, existing research often focuses on isolated measures and does not completely reflect the changes under the FO 2017.

An expert group evaluated the FO 2007 on behalf of the Federal Ministry on Food and Agriculture and suggested possible improvements (Osterburg & Techen 2012). Numerous recommendations of the group are reflected in the revised FO. The report represents the most recent and comprehensive analysis of the FO 2007 and its shortcomings. Moreover, it gives insides into possible impacts of revised measures. For the evaluation, the group mainly uses farm-level control data reported from few federal states and data from the Farm Structure Survey (FFS).

The latter allows calculating regional nutrient excretion and balances on community level by combining farm structure data with standard factors for animal excretion and plant removal. Osterburg & Techen (2012, pp. 211ff.) analyze the organic N threshold and the N and P_2O_5 surplus simultaneously as one threshold becomes binding first and leads to meeting the other thresholds likewise. The authors show that the P_2O_5 surplus restriction and the organic N application threshold become binding before the N surplus on the regional level. Thereby, the P surplus is found to be most binding in North-West Germany whereas in the forage growing dominated regions (South Germany, Lower Saxony and North Rhine Westphalia) the organic N application threshold limits the application. The authors find that the P_2O_5 surplus prevention on highly enriched soils increases the share of the total German manure production, which needs to be exported out of communities, from 1.5% to almost 4%. Also research on investment strategies of typical pig farms under different restrictions, not reflecting the exact changes of the FO 2017 but general water protection policies, shows that the P_2O_5 surplus is most binding for manure application and restricting the surplus to zero lowers farm income (Budde 2013, pp. 124ff.). The results indicate the huge impact of the measures regarding P_2O_5 surpluses in the FO 2017. Furthermore, they hint at which thresholds are most binding on farm-level as the same relation of nutrient removal and input are present. Generally, the need to reduce surpluses will be higher on farm-level than the analysis on community level suggests.

The evaluation of an unrepresentative sample of farm nutrient balances, coming from control organizations in six federal states, gives insides into reasons for nutrient balance surpluses at farm-level and the impact of methodological changes under the FO 2017. Around 20% of the farms subject to research exceeded the N and P_2O_5 surplus restriction under the FO 2007. Surpluses are found in farms with low and high amounts of organic nutrient input per ha (Osterburg & Techen 2012, pp. 185ff.). Hence, they are not only caused by high stocking densities and are also present on arable farms. Osterburg & Techen (2012, pp. 195f.) highlight, amongst others, the importance of management and the existing potential to increase N use efficiency. They found that grouped farms with similar structure, meaning mainly the same nutrient removal with the harvest and organic N input, have a standard deviation of chemical N fertilizer input between 30 and 50 kg N ha^{-1}. The implementation of the compulsory fertilizing planning in the FO 2017 aims at closing the existing efficiency gaps.

Generally, nutrient surpluses are highest in livestock fattening farms and lowest in forage growing farms. The latter is mainly caused by the overestimation of the nutrient removal with on farm grown forage (Osterburg & Techen 2012, pp. 187ff.). Under the FO 2017, nutrient removal via forage production is estimated based on the feed need of the present animal stock. This will lead to an increase of the N surplus of farms which have overestimated their forage yield before. In the data examined by Osterburg & Techen (2012, pp. 191), 25% instead of 10% forage growing farms in the sample exceed the threshold of 60 kg N ha^{-1} when following the new balance approach. However, the data does not allow any conclusions with regard to the enforcement of the surplus as it mainly comes from past years when higher surpluses were still allowed. Osterburg & Techen (2012, p. 187) conclude that farms which exceed the threshold for the N balance can adapt by reducing external N fertilizer inputs. They in contrast argue that farms exceeding the P_2O_5 surplus usually have little options to reduce chemical P_2O_5 fertilizing, possible adaption strategies being instead P-reduced feeding and the increase of P_2O_5 removal by straw export.

The prolongation of banning periods under the FO 2017 shifts manure application to spring. Osterburg & Techen (2012, pp. 169ff.) estimate that in 2010 around 30% of the total excreted manure was applied between April and October, mainly after the harvest of the main crop. They conclude that around 20% to 25% of the manure is affected by stricter banning periods on arable land under the FO 2017. Assuming an increase of N efficiency due to higher N use in spring, the authors state that these measures lead to a decrease of N surplus from 3 to 4 kg N ha^{-1} on a regional scale. The prolongation of the banning period is strongly connected to the minimum storage capacity. Farms exceeding 3 LU ha^{-1} need to increase their manure storage capacity from 6 to 9 months. In 2007, around 45% of the LU in Germany were kept in farms which had already capacities for more than 6 months as shown by Osterburg & Techen (2012, pp. 174f.). The authors conclude that by now a large share of farms already holds higher storage capacities than required by law in the past. As more recent data was not available and the presence of storage capacity could not be linked to the LU density, it is not possible to estimate the share of current compliance precisely.

The introduction of low NH_3 emissions application is characterized by the fading out of broadcast spreading. Osterburg & Techen (2012, pp. 177f.) use data from 2010 to show that around 50% of the total manure is applied to grassland or covered land by broadcast spreader. The authors find that on grassland, around 90% of the manure was applied with broadcast spreader. Hence, the restrictions under the FO 2017 will especially affect grassland based livestock production. With regard to the incorporation of manure on bare land, data show that in 2010 around 25% of all farms incorporate manure faster than one hour and around 40% between one and four hours (Osterburg & Techen 2012, p. 180).

In several federal states, reports on regional nutrient balances and manure transport are published frequently (e.g. LWK NRW 2014; LWK Nds. 2017). In comparison to the regional nutrient balances calculated by Osterburg & Techen (2012), they take already existing manure flows within and between communities into account. The reports focus on characterizing the status quo under the FO 2007. The recent report from Lower Saxony, however, also includes projections on future regional nutrient excess after the implementation of the FO 2017. Results show that seven instead of four counties (NUTS 3) exceed the allowed P_2O_5 surplus when it is lowered from 20 to 10 kg P_2O_5 ha^{-1}. This increases the area need for manure application outside of surplus counties to 120,000 ha. The inclusion of all organic N fertilizer in the organic N application limit leads to the exceeding of the threshold in seven instead of one county (LWK Nds. 2016, pp. 25ff.). The calculation does not fully reflect the upcoming changes as the reduction of P_2O_5 surplus on highly enriched soils, possible reduction of allowed surpluses in polluted areas and methodological changes of the nutrient balance calculation are missing. However, the results indicate the large impact of the changes in the FO 2007 regarding P_2O_5 surpluses and illustrate the upcoming need for farmers to adapt.

There is no literature on the detailed reduction of different emissions realized by the revised FO. To fulfil the Directive on the assessment of the effects of certain plans and programmes on the environment (Europäisches Parlament; European Council 2001), the impact was evaluated qualitatively in the context of a strategic environmental assessment (BMEL 2016), using mainly results from Osterburg & Techen (2012). The German Government’s Climate Action Programme 2020 budgets a contribution of agriculture to the overall reduction efforts. Thereby, the biggest part, 3.3 Mio t CO_2 equivalents, should be realized by the revision of the FO (BMUB 2014, pp. 59ff.). With regard to NH_3 emissions, older estimations assume a reduction of around 45 Gg NH_3 due to the implementation low emission manure application techniques. As total NH_3 emissions are reported at 540 Gg in 2015 by the study, this represents a relevant reduction (UBA 2014, pp. 99f.). A report published by the German Working Group of the Federal States on Water Issues assumes a reduction of the N input to groundwater and surface water bodies of 30% in pollution hotspots and 10% area-wide

(LAWA 2014, pp. 24f.). However, due to methodological limitations and incomplete reflection of the FO 2017, these figures are highly insecure.

2.4 Conclusion

In Germany, the FO is the core legislation to limit nutrient emission from agriculture to the environment. It implements the Nitrates Directive and contributes to achieving environmental targets laid down in several other regulations. This chapter summarizes the most important changes under the current revision of the FO and the existing research. The FO 2017 comprises stricter regulations than the FO 2007, causing most probably efforts of farms to comply and a considerable reduction of the pressure on the environment. Generally, there is little research on the revision available.

Existing literature hints at an increasing need to lower nutrient surpluses at the farm and regional level, especially with regard to P_2O_5. This will, among other, lead to an increased manure transport and, most likely, to a boost of manure processing techniques. The transport of manure includes the risk of increasing emissions in the manure importing regions. This regional pollution swapping has been rarely discussed in the revision process and research on its prevention is needed, especially with regard to regional differentiation of measures. However, manure transport is just one adoption strategy of farmers to comply with stricter surplus restrictions. In comparison to static calculations, as applied in the existing research, economic optimization approaches can help to include farmers' behavior when facing stricter regulations and to identify possible cost-efficient compliance strategies.

Generally, more research on the environmental impact of the revised FO is needed. A precise reduction of the abated emissions is of special importance to quantify the contribution to existing environmental targets and to identify further needs for reduction. This is for example crucial to estimate the remaining reduction need to fulfill the WFD. The FO serves as a basic measure to reach the targets of the directive. Further reduction is realized mainly by voluntary agri-environmental measures which should be designed complementary to the FO.

The impact of the revision is highly depending on the enforcement of the regulations. Existing research usually assumes that the measures are fully applied. However, empirical results hint a lack of enforcement in the past. The revised FO comprises several elements which allow a better controlling of regulations, as for instance higher penalties or better data access for enforcing institutions. The detailed implementation of the FO is depending on the federal states and remain to be seen in the future. The same holds true for existing vagueness of the directive which institutions on the federal level have to specify. Besides uncertainty with regard to the enforcement and detailed implementation, the design and impact of the derogation is still uncertain.

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Chapter 3

A farm typology for North Rhine-Westphalia to assess agri-environmental policies[2]

Abstract

The use of farm models to analyze agri-environmental policies requires selecting farms which can be hypothetical, typical or observed ones. Farm typologies, understood as a grouping of farms according to relevant farm characteristics, allow selecting most prevailing farm types for a modelling exercise. Thereby, a farm type represents a share of the real-word farm population. We develop a farm typology for the German Federal State of North Rhine-Westphalia based on the Farm Structure Survey 2016. It is designed to assess the revision of the German fertilization regulations in 2017 by applying a combination of a bio-physical crop model and a bio-economic farm model. The derived typology covers 77% of farms in North Rhine-Westphalia and comprises 210 farm types. Farms are grouped according to specialization, size in relation to area, and stocking density. In addition, a typical crop rotation is defined for every specialization in the nine soil-climate regions of North Rhine-Westphalia. We show that the proposed typology provides the necessary information for the selection of farm types as well as for the model initialization and parameterization in the described modelling exercise. Furthermore, we provide the information to adapt and extent the typology to similar research questions and upcoming Farm Structure Surveys. The incorporation of expert knowledge to identify farm structures which are not captured by the official statistic could improve the typology.

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3.1 Introduction

A vast number of farm (level) models emerged in the last years and is frequently used in policy analysis with various foci (Reidsma *et al.* 2018, pp. 113f.). Their strength is, amongst others, the ability to capture heterogeneity across farms and the interaction between different farming activities, the environmental impact and the economic performance (Blanco 2016, p. 2). However, a crucial decision is the selection of the modelled farms. Based on the research focus and data availability, different approaches exist. First, studies dealing with more general research questions tend to assess hypothetical farms, typically derived from a thin data base and expert knowledge, and not from a known farm population (e.g. Lengers *et al.* 2013, p. 460). Second, application of farm models to case studies typically cover exemplary farms (e.g. van Calker *et al.* 2004, pp. 149f.). Third, farm models can be applied to farms selected from a typology (e.g. Belhouchette *et al.* 2011, p. 138) or, forth, for a representative sample of a farm population (e.g. Mack & Huber 2017, p. 35).

A farm typology is understood as a grouping of farms according to farm characteristics which are of importance for the addressed research question. Thereby, every derived group of farms within the typology forms a so-called farm type. Hence, a modelled farm related to such a farm type is thought to represent a number of real-world farms of the underlying data.

There are two basic methodological approaches in literature with regard to farm typologies: the expert approach and the analytical approach (Mądry *et al.* 2013, p. 320). In some cases, both approaches are combined (e.g. Caballero *et al.* 2008, pp. 191f.). The expert method relies both on official statistics and expert knowledge. When comparing studies using that approach, two partly overlapping groups can be found. The first one uses expert knowledge to arrange farms into groups and relies on official statistics for farm characteristics (e.g. Gocht & Britz 2011, pp. 149f.; Andersen *et al.* 2007, pp. 355ff.). The second group uses expert knowledge in addition as a relevant data source for farm characteristics (e.g. Zimmer & Deblitz 2005, p. 2; Budde 2013, p. 87). In studies following the analytical approach, statistical methods such as combinations of factor and cluster analysis are used for grouping farms (e.g. Köbrich *et al.* 2002, pp. 143f.; Sierra *et al.* 2017, p. 174).

This chapter provides an expert-based farm typology for the German Federal State of North Rhine-Westphalia (NRW). The typology is used to assess the revision of the German Fertilization Ordinance (FO) in 2017 (BMEL 2017) with the bio-economic farm-scale optimization model Farmdyn (Britz *et al.* 2018). For this purpose, Farmdyn is connected to the bio-physical crop modelling framework Simplace (Gaiser *et al.* 2013, p. 7) which requires the regional location of farm types to define soil and climate conditions. The derived farm typology firstly allows selecting the most frequent farm types for the modelling exercise. Secondly, it enables assessing the relative importance of selected farm types in the farm population when modelling the most affected instead of the most frequent farms. Thirdly, it provides necessary variables and parameters for the modelling exercise.

The presented farm typology is largely based on the German Farm Structure Survey (FSS) from 2016 which provides single farm data for all farms in Germany above a minimum threshold size. However, the use of single farm data is subject to strict data protection standards (Statistische Ämter des Bundes und der Länder 2017, pp. 16 ff.) to which the developed typology adheres. The study at hand provides all necessary information to easily renew the typology for upcoming FSS or extend the typology to address different research questions. Hence, it can serve as a guideline for the future use of the FSS.

The chapter is structured as follows: Section 3.2 introduces the developed farm typology and the used data sources. In Section 3.34.3.2, the results of the farm typology are exemplarily presented for specialized cereal and pig fattening farms. Section 3.4 briefly discusses the typology and concludes. The Appendix contains extended results of the typology.

3.2 Concept of farm typology

To derive a farm typology for NRW, we adapt the methodology applied by Andersen *et al.* (2007). Farm types are created by grouping farms from official agricultural statistics with regard to relevant farm characteristics. The definitions of the groups are based on expert knowledge, whereas the farm characteristics are derived from official statistics.

3.2.1 Data Source

The typology is based on the FSS which is conducted every three to four years (Hauschild *et al.* 2017, p. 75). The FSS is carried out in the whole EU by member states using a harmonized approach and reported to Eurostat (Eurostat 2018). We rely on the FSS of 2016. It covers all farms of NRW registered as legal entities above a defined size and provides numerous farm characteristics, such as cropping shares, animal stock or work force, as well as the farm location at community level (Destatis n.d.). The use of FSS is governed by strict data protection standards which prevent direct data access. Instead, researchers have to provide their statistical scripts to the Research Data Centers of the Federal Statistical Office and the statistical offices of the states. The institutions review the script, run it themselves and carefully check its output, mainly to prevent the later identification of single farms. If data protection requirements are met, the output is handed to the researcher. However, it might still be partly blanked if for instance selected data refer to three or less real farms.

3.2.2 Farm grouping

All farms in NRW are grouped according to (1) specialization (2) farm area, and (3) stocking density (Figure 3.1). Thus, following Andersen *et al.* (2007, p. 355), an existing typology on specialization of farms from official agricultural statistics is extended. The FSS groups farms according to their main farming activities which are defined based on the relative contribution of standard output coming from certain farming activities following the EU typology of 2008 (European Commission 2008). Standard output is defined as "the standard value of gross production" (European Commission 2008, p. 4). A specialist pig fattening farm, for instance, realizes more than 2/3 of its standard output with fatteners (Appendix 3.A). The EU typology distinguishes a total of 61 specializations. However, we exclude 44 specializations from the typology as they are neither relevant for the study area nor of interest for the assessed research question.

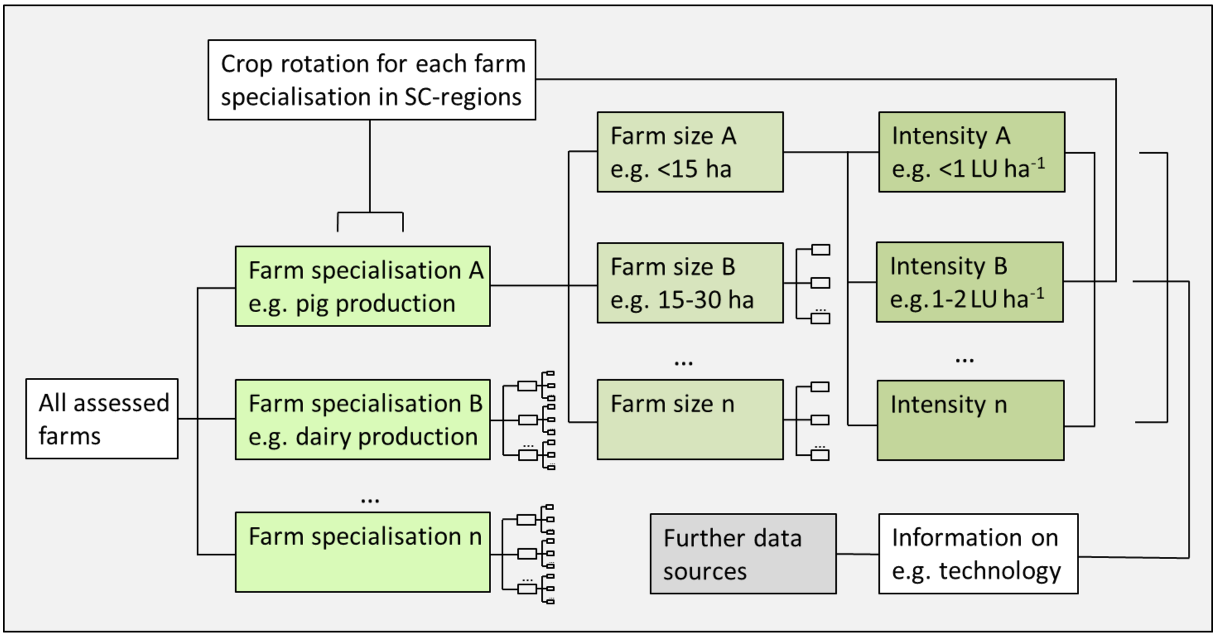

Figure 3.1 Concept of the farm typology

Source: own illustration; LU - livestock units; SC-regions - soil-climate regions

Farms of a certain specialization are further grouped according to their farm area in hectare as farm size influences profits and is potentially related to economies of scale. Regarding the assessment of the FO, this can be relevant for the costs of introducing low-emission manure application techniques or additional manure storage. Breaks between groups are defined with the help of descriptive statistics, aiming at homogeneity within groups and heterogeneity between groups. Four groups of different farm sizes are selected whereby group limits differ between specializations. In the next step, farms are further grouped according to their stocking density in livestock units (LU) per hectare. Stocking density is a relevant farm characteristic when assessing the impact of agri-environmental policies such as the German

FO. Farms with higher stocking density face higher efforts and costs to fulfil measures like nutrient application thresholds or requirements concerning the manure storage capacity which are directly linked to the stocking density. Depending on the specialization, two to four categories of stocking density are defined.

3.2.3 Farm location and crop rotation

The farm typology is developed for a modelling setup which combines a bio-economic farm model and a biophysical crop model. The latter simulates crop rotations under different management and soil-climate conditions. It captures relevant bio-physical flows of crops and corresponding environmental parameters (Gaiser *et al.* 2013, p. 7f.). Inter alia, information on the crop rotation of farm types is needed to run the modelling setup. The prevalent crop rotations depend on climatic and soil conditions. Accordingly, farms in the sample are grouped into predefined soil-climate regions (SCRs). The concept of SCRs has been developed by Roßberg *et al.* (2007) with the goal of harmonizing typologies used in different agricultural institutions for field variety trials and pesticide monitoring. Every of the around 400 communities in NRW is assessed with regard to soil quality and climate. Based on a cluster analysis and expert judgement, homogenous communities form a SCR (Roßberg *et al.* 2007, pp. 156ff.). Hence, SCRs are consistent to the community level which allows a precise interlinkage to the FSS. NRW consists of nine SCRs as shown in Figure 3.2 whereas five SCRs cover the bigger part of the land area.

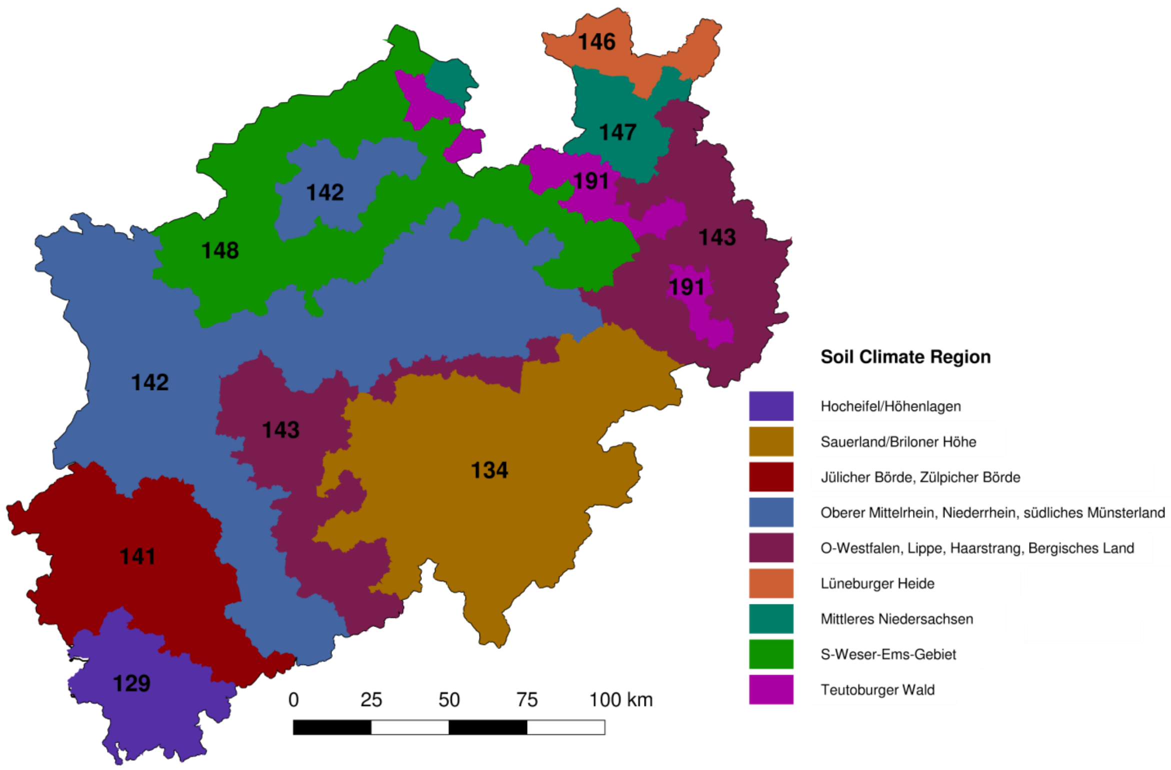

Figure 3.2 Overview on soil-climate regions in North Rhine-Westphalia

Sources: own illustration based on the typology from Roßberg et al. (2007) and data provided by GeoPortal.JKI (n.d.)

In a next step, crop shares are derived for all specializations and each SCR from the FSS 2016 and from the Census of Agriculture 2010. For some combinations of specialization and SCR, the crop shares derived from the FSS 2016 are blocked due to data protection standards. Partly, data from the Census of Agriculture 2010 are accessible for these combinations and used instead (see Appendix 3.E for details). Depending on the crop shares and based on expert judgement, one dominant crop rotation is defined for each specialization in each SCR (Gaiser 2018). Unlike farm area or stocking density, crop rotations are not included in the typology as a further farm characteristic for two reasons. First, we could not find a relevant variation of crop shares between farms of different size and stocking density within a specialization. Second, a further differentiation increases the number of farm types in the typology tremendously and leads to the blocking of a higher share of the data output due to the data protection standards.

3.3 A farm typology for NRW

The derived farm typology covers 25,914 farms and thus around 77% of all farms in NRW. Horticulture, specialist permanent crops, grazing livestock other than cows and poultry are the specializations of farms not captured by the typology. In the following sections, the results of the typology are exemplary presented for ten specialized pig fattening farm types and farm types specialized in cereals (other than rice), oilseeds and protein crops (in the following called specialized cereal farms). The selected farm types are the most prevalent ones with regard to farm numbers. In the Appendix 3, 100 farm types of the typology are presented. Each of the remaining 110 farm types represents less than 40 farms and numerous farm characteristics are blocked in the data output due to the low number of observations for those farm types.

3.3.1 Farm importance

The developed farm typology allows assessing the relative importance of farm types in the population. Importance can be defined as (1) share of total farms covered by a farm type, (2) share of total agricultural land covered by a farm type and, (3) share of livestock covered by a farm type. Table 3.1 exemplary presents the results on farm importance for specialized cereal and pig fattening farm types (see Appendix 3.B for full results).

Specialized cereal farms with less than 50 ha and a livestock density between 0 and 0.2 LU ha^{-1}, for instance, are highly frequent in the farm population with a share of 8.09% of all farms in NRW. However, due to their small size, they cover only 3.80% of the agricultural land. In opposite, specialized cereal farms between 50 and 100 ha with 0 to 0.2 LU ha^{-1}, only cover 1.78% of farms but account for 2.90% of the agricultural land.

Table 3.1 Most frequent specialized cereal and pig fattening farm types in NRW

Farm type	Share of farm area	Share of farm numbers	Share of livestock units	Share of dairy cows	Share of fattening pigs
Specialized cereal farm[a] <50 ha, >0.2 LU ha^{-1}	0.36%	0.76%	0.11%	0.00%	0.01%
Specialized cereal farm[a] <50 ha, 0-0.2 LU ha^{-1}	3.80%	8.09%	0.04%	0.00%	0.01%
Specialized cereal farm[a] >200 ha, 0-0.2 LU ha^{-1}	-	0.20%	-	-	-
Specialized cereal farm[a] 100-200 ha, 0-0.2 LU ha^{-1}	2.35%	0.76%	0.03%	-	-
Specialized cereal farm[a] 50-100 ha, 0-0.2 LU ha^{-1}	2.90%	1.78%	0.04%	-	0.02%
Pig fattening farm[b] <20 ha, >3 LU ha^{-1}	0.08%	3.85%	8.52%	-	26.15%
Pig fattening farm[b] 20-50 ha, 1-2 LU ha^{-1}	0.63%	0.75%	0.80%	-	2.49%
Pig fattening farm[b] 20-50 ha, 2-3 LU ha^{-1}	0.92%	1.07%	1.80%	-	5.79%
Pig fattening farm[b] 50-100 ha, 1-2 LU ha^{-1}	-	1.26%	-	0.00%	8.99%
Pig fattening farm[b] 50-100 ha, 2-3 LU ha^{-1}	-	0.96%	-	-	8.63%

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation.; "-" indicates values which are blocked due to data privacy requirements; [a] specialist cereals (other than rice) oilseeds and protein crops (151); [b] specialist pig fattening (512); LU - livestock units

For livestock farms, the share of animals covered by a farm type is an additional indication for farm importance. 26.15% of the assessed pig stock is found in pig fattening farms with less than 20 ha and more than 3 LU ha^{-1}. However, these farms are to some extent part of a bigger farm unit which is separated amongst other for tax optimization. That limits the validity of the developed farm typology especially in case of pig farms (Section 3.4). Pig fattening farms with 50 to 100 ha cover a relevant share of farm numbers and pig stock. 8.99% of the pig stock in NRW can be found in this size class for a livestock density between 1 and 2 LU ha^{-1} and 8.63% of the pig stock for a livestock density between 2 and 3 LU ha^{-1}.

3.3.2 Farm characteristics

For the developed farm types, farm characteristics are extracted from the FSS. For all farms summarized as a farm type, we calculate the median of the selected farm characteristics. Characteristics are chosen in accordance to the assessment of the FO being livestock numbers (total livestock, dairy cows, pigs, sows), arable land area, grassland area, and livestock density. Table 3.2 exemplary shows the farm characteristics for the most frequent specialized arable and pig fattening farm types (see Appendix 3.C for full results).

Table 3.2 Median of farm characteristics of the most frequent specialized cereal and pig fattening farm types in NRW

Farm type	Total livestock units [LU]	Pig [LU]	Arable land [ha]	Grassland [ha]	Livestock density [LU ha^{-1}]
Specialized cereal farm[a] <50 ha, >0.2 LU ha^{-1}	7.00	0.00	14.00	3.00	0.36
Specialized cereal farm[a] <50 ha, 0-0.2 LU ha^{-1}	0.00	0.00	14.96	0.50	0.00
Specialized cereal farm[a] >200 ha, 0-0.2 LU ha^{-1}	0.00	0.00	233.50	4.89	0.00
Specialized cereal farm[a] 100-200 ha, 0-0.2 LU ha^{-1}	0.00	0.00	119.11	3.00	0.00
Specialized cereal farm[a] 50-100 ha, 0-0.2 LU ha^{-1}	0.00	0.00	62.40	1.96	0.00
Pig fattening farm[b] <20 ha, >3 LU ha^{-1}	106.54	103.26	0.00	0.00	4.60
Pig fattening farm[b] 20-50 ha, 1-2 LU ha^{-1}	56.40	54.00	33.58	0.68	1.64
Pig fattening farm[b] 20-50 ha, 2-3 LU ha^{-1}	93.60	92.40	36.00	0.00	2.46
Pig fattening farm[b] 50-100 ha, 1-2 LU ha^{-1}	118.44	117.60	71.00	1.00	1.68
Pig fattening farm[b] 50-100 ha, 2-3 LU ha^{-1}	149.82	148.32	61.67	0.35	2.30

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [a] specialist cereals (other than rice) oilseeds and protein crops (151); [b] specialist pig fattening (512); LU - livestock units

Specialized cereal farms with less than 50 ha and more than 0.2 LU ha^{-1}, for instance, have a size of 14 ha and livestock density of 0.36 LU ha^{-1} as median. Pig fattening farms are characterized by higher stocking densities. Pig farms with less than 20 ha and more than 3 LU ha^{-1} do not hold any land in the median and have a median of 4.60 LU ha^{-1} as stocking density. The second most present pig farm type, 20 to 50 ha and 1 to 2 LU ha^{-1}, has a median of 33.58 ha and 1.64 LU ha^{-1}. The median of pig and total LU is almost equal which indicates that other livestock than pigs is rarely present. The grassland area is, as for all pig fattening farm types in Table 3.2, very low. None of the most frequent pig farm types, except the farms which to some extent are part of a bigger farming unit, exceeds 2.5 LU ha^{-1}.

3.3.3 Farm location

As explained, all farms present in the FSS can be located in a SCR. This allows deriving the distribution of farm types in the nine SCRs of NRW. Table 3.3 exemplary shows the distribution of the most frequent specialized cereal and pig fattening farm types in the SCRs (see Appendix 3.D for full results).

Specialized cereal farms with less than 50 ha and more than 0.2 LU ha^{-1}, for instance, are found mainly in SCR 142 with 30.42%, SCR 143 with 23.44%, and SCR 148 with 22.27%. Pig fattening farms with 20 to 50 ha and 1 to 2 LU ha^{-1} are also most frequent in SCR 142 with 41.34% and SCR 148 with 37.01%. The distribution of the farm types in the SCRs is on the one hand caused by the size of the SCR and on the other hand by the comparative advantage of certain agricultural activities under certain climate and soil conditions.

Table 3.3 Farm location of the most frequent specialized cereal and pig fattening farm types in NRW

Farm type	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191
Specialized cereal farm[a] <50 ha, >0.2 LU ha^{-1}	1.56%	5.86%	2.34%	30.47%	23.44%	2.34%	6.64%	22.27%	5.08%
Specialized cereal farm[a] <50 ha, 0-0.2 LU ha^{-1}	1.72%	5.06%	5.47%	25.61%	18.83%	6.72%	10.02%	22.68%	3.89%
Specialized cereal farm[a] >200 ha, 0-0.2 LU ha^{-1}	2.99%	8.96%	14.93%	31.34%	32.84%	2.99%	1.49%	0.00%	4.48%
Specialized cereal farm[a] 100-200 ha, 0-0.2 LU ha^{-1}	9.02%	5.88%	16.08%	24.71%	26.67%	0.78%	4.31%	7.84%	4.71%
Specialized cereal farm[a] 50-100 ha, 0-0.2 LU ha^{-1}	2.67%	6.83%	9.00%	32.83%	21.67%	3.33%	6.83%	12.50%	4.33%
Pig fattening farm[b] <20 ha, >3 LU ha^{-1}	0.00%	3.86%	1.00%	37.50%	6.79%	2.55%	2.62%	43.90%	1.77%
Pig fattening farm[b] 20-50 ha, 1-2 LU ha^{-1}	0.00%	3.15%	0.00%	41.34%	6.30%	5.51%	3.94%	37.01%	2.76%
Pig fattening farm[b] 20-50 ha, 2-3 LU ha^{-1}	0.00%	2.22%	0.00%	39.89%	4.16%	2.22%	2.77%	46.81%	1.94%
Pig fattening farm[b] 50-100 ha, 1-2 LU ha^{-1}	0.24%	6.86%	0.47%	33.10%	15.37%	4.26%	4.96%	32.15%	2.60%
Pig fattening farm[b] 50-100 ha, 2-3 LU ha^{-1}	0.62%	2.80%	0.00%	39.44%	5.28%	3.42%	1.55%	44.41%	2.48%

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [a] specialist cereals (other than rice) oilseeds and protein crops (151); [b] specialist pig fattening (512); LU - livestock units; SCR - soil-climate region

As described above, the farm typology defines the most present soil and climate conditions for the developed farm types. In addition, it allows extracting the most present farm types in the nine SCRs which is exemplarily shown in Table 3.4 for SCR 129. For a total of 674 farms, 11.78% are specialized in growing a combination of various field crops and have less than 50 ha and no animal stock. The second most present farm type are small cattle farms (less than 20 ha and 0 to 1 LU ha^{-1}) with 9.35%. The most present farm types can be derived for all SCRs based on the data provided in Appendix 3.D.

Table 3.4 Most frequent farm types in soil-climate region 129

Farm type	Size and livestock density	SCR 129
Total farm numbers		674
Various field crops combined (166)	<50 ha, 0-0.2 LU ha^{-1}	11.87%
Specialist cattle - rearing and fattening (460)	<20 ha, 0-1 LU ha^{-1}	9.35%
Specialist dairying (450)	>100 ha, 1-2 LU ha^{-1}	8.90%
Specialist dairying (450)	50-100 ha, 1-2 LU ha^{-1}	8.01%
Specialist cereals (other than rice) oilseeds and protein crops (151)	<50 ha, 0-0.2 LU ha^{-1}	6.97%
Specialist cattle - rearing and fattening (460)	<20 ha, 1-2 LU ha^{-1}	6.53%
Specialist cattle - rearing and fattening (460)	20-50 ha, 0-1 LU ha^{-1}	5.79%
Specialist dairying (450)	50-100 ha, 0-1 LU ha^{-1}	4.45%
Specialist cereals (other than rice) oilseeds and protein crops (151)	100-200 ha, 0-0.2 LU ha^{-1}	3.41%
Specialist dairying (450)	20-50 ha , 1-2 LU ha^{-1}	2.97%

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; SCR - soil-climate region

3.3.4 Crop rotations

For all farming specializations and SCRs, crop rotations are defined based on the crop shares derived from the FSS. Table 3.5 exemplary illustrates the derived crop rotations for the most present specialized cereal and pig fattening farms (see Appendix 3.E for full results).

Table 3.5 Crop rotations of specialized cereal and pig fattening farm types in the different soil-climate regions of NRW

Specialization	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191
Specialized cereal farm[a]	WW	WW	WW	WW	WW	-	WW	WW	WW
	WB	WB	WB	WB	WB		WB	KM	WB
	WR[d]	WR[c]	WR[c]	WR[c]	WR[c]		WR[c]	KM[c]	WR[c]
Pig fattening farm[b]	-	-	WW	WW	WW	-	-	WW	-
			WB	WB	WB			WB	
			ZR[d]	CCM[c]	WTr			CCM	
					WR[d]			CCM[c]	

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender, Farm Structure Survey, 2016, own calculation (crop rotations marked with [c]), RDC of the Federal Statistical Office and Statistical Offices of the Laender, Census of Agriculture, 2010, own calculation (crop rotations marked with [d]), Gaiser (2018); [a] specialist cereals (other than rice) oilseeds and protein crops (151); [b] specialist pig fattening (512); CCM - corn-cob-mix; KM - grain maize; SB - sugar beet; SCR - soil-climate region; SM - silage maize; WB - winter barley; WR - winter rapeseed; WTr - winter triticale; WW - winter wheat

Specialized cereal farms, for instance, grow crop rotations dominated by winter wheat and winter barley. Only in SCR 148, grain maize dominates the crop rotation. Pig fattening farms grow more diverse rotations in the different SCRs, for instance winter wheat, winter barley and sugar beet in SCR 141 and winter wheat, winter barley and corn-cob-mix in SCR 148.

3.4 Discussion and Conclusion

We provide a farm typology for NRW based on single farm data from the FSS. Farms are grouped according to specialization, size in hectare and livestock density. Furthermore, a dominant crop rotation is defined for the combination of all assessed farm specializations and the nine SCRs in NRW. The typology provides important variables to the initialization (e.g. stocking density) and parameterization (e.g. specialization, farm size) of farm models to assess the revision of the German FO.

We adopt the methodology developed by Andersen *et al.* (2007) within the SEAMLESS project (van Ittersum *et al.* 2008). Following Mądry *et al.* (2013, p. 320), the methodology can be characterized as an expert approach with a strong use of agricultural statistics. In contrast to Andersen *et al.* (2007, p. 354), we use the FSS instead of the Farm Accountancy Data Network (FADN) as the main data source. This has the advantage of a higher coverage of farms and more detailed information on farm location. The latter is of importance for a consistent linkage of the location of farms to SCRs. However, FADN covers more economic parameters than the FSS. The typology defines in total 210 farm types for NRW. This is in the same range as the typology developed by Andersen *et al.* (2006, p. 6) which results in

189 farm types. Generally, there is a trade-off between segregation and generalization in farm typologies. More segregated typologies reflect better heterogeneity and result in farm types closer to real-world farms. However, that leads to a lower number of real-world farms represented by a farm type and, hence, more blocked data output due to data protection standards. A more general farm typology facilitates the selection of the most relevant farm types for further analysis and the communication of results to stakeholders.

The FSS accounts legal units as one farm. However, farms frequently consist of numerous legal units or numerous farms are combined to one legal unit for tax optimization and other reasons. Such complex structures primarily are motivated by the avoidance of the status as a commercial farm which impacts the tax burden (Forstner & Zavyalova 2017, p. 13). In NRW, complex holding structures of farms are hardly recognizable from official agricultural statistics (Forstner & Zavyalova 2017, pp. 33ff.) and are not reflected in the derived typology. This can result in misleading outcomes when selecting such farm types for the modelling exercise. For the most present specialized pig farm type with high stocking density, for instance, a farm-level model will return high compliance costs to fulfil environmental regulations such as the German FO because of high costs to export excess manure. If such farms are part of a bigger farming unit, excess manure is, at least partly, only transported within the bigger unit which results in lower costs.

Compared to a farm typology which relies on expert knowledge for the judgement of farm characteristics (e.g. Budde 2013, p. 87), the typology in the chapter at hand is transparent with regard to data sources and covers all farms with the specializations of interest. However, complex farm structures beyond legal units may be better captured by expert judgement. Furthermore, a typology based on the FSS or FADN does not provide all farm characteristics needed to parameterize farm models for detailed analysis of environmental policies. Therefore, such typologies are also complemented by expert knowledge. For the modelling exercise, we need additional expert judgement for current farm management which is not covered in detail in the FSS. Furthermore, we strongly rely on expert knowledge to derive the crop rotations from the observed crop shares for the developed farm types. However, this process can be improved by using optimization models to detect the crop rotations with the highest coverage of cropped land (e.g. Schönhart *et al.* 2011).

We conclude that the developed farm typology provides the necessary information to select relevant farms, understood as most frequent or affected, to assess the revision of the FO in Germany with farm models. Furthermore, it contains important input variables for the initialization and parameterization of such models. The chapter at hand allows to select farms and corresponding farm characteristics for similar research questions as well as to easily extent and update the typology with future FSS. The typology can be improved by the inclusion of expert knowledge to detect farm structures beyond legal units which are not covered in agricultural statistics.

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Chapter 4

Coupling crop and bio-economic farm modelling to evaluate the revised fertilization regulations in Germany[3]

Abstract

The German Fertilization Ordinance (FO), implementing mainly the EU Nitrates Directive, was revised in 2017. We couple the bio-economic farm model FarmDyn and the crop system modelling framework SIMPLACE to assess the environmental and economic impact of the revised ordinance. The analysis focuses on specialized pig fattening and arable farms in the federal state of North Rhine-Westphalia. Most dominant farm types are derived from a farm typology based on the German Farm Structure Survey (FFS) 2016. Following the revised ordinance, a farm type representing pig farms with a high stocking density lowers its emissions from 50 to 38 kg nitrate (NO_3^-) nitrogen ha^{-1} and 18 to 8 kg ammonia (NH_3) nitrogen ha^{-1} from manure application. Compliance costs are 2.32 Euro (€) pig^{-1} and are mainly caused by the need to export manure to meet the stricter nutrient surplus thresholds. A pig farm type with lower stocking density mainly adapts to the compulsory use of low-emission manure application techniques, resulting in almost constant NO_3^- leaching, a NH_3 reduction from manure application of 13 to 9 kg NH_3-nitrogen ha^{-1}, and compliance costs of 0.42 € pig^{-1}. The two assessed arable farm types, which start to import manure under the revised ordinance, can lower costs by 97 and 108 € ha^{-1}. However, manure import increases NO_3^- leaching and NH_3 volatilization. Our results show that intensive pig farms realize a high emission reduction and lose a relevant share of their standard gross margin when complying with the revised ordinance. However, farm types with low stocking density, representing a high share of the pig farms in the study area, show little or no changes in costs and emissions. These findings are relevant for efficient enforcement and targeted support measures. Furthermore, the import of manure on arable farms comprises the danger of

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[3] This chapter is based on joint work in the research project "Modeling structural change and agricultural nutrient flows across scales in regions of North Rhine-Westphalia". Andreas Enders, Dr. Thomas Gaiser und Dr. Amit Kumar Srivastava provided the SIMPLACE simulations and wrote Chapter 4.2.2 and 4.4.3 as well as the Appendices 4C, 4D, 4E, 4F, and 4G. This chapter is published in a previous version in Agricultural Systems, 177, Kuhn, T., Enders, A., Gaiser, T., Schäfer, D., Srivastava, A.K., Britz, W., Coupling crop and bio-economic farm modelling to evaluate the revised fertilization regulations in Germany, Copyright Elsevier (2020). Online available at https://doi.org/10.1016/j.agsy.2019.102687. The research is funded by the Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (MULNV) within the framework of the teaching and research focus "Umweltverträgliche und Standortgerechte Landwirtschaft" (USL).

regional pollution swapping, which policymakers should address by complementary measures. Future research should focus on improving the data base for crop modelling and on scaling-up the farm model to the regional scale to directly link emission changes and environmental targets.

4.1 Introduction

Bio-economic farm models capture farm heterogeneity and interactions between farm management and the environment (Blanco 2016, p. 2) based on input-output relations of farming activities and corresponding externalities (Janssen *et al.* 2010, p. 863). Thereby, they are able to identify trade-offs between economic and environmental goals (Ruben *et al.* 1998, p. 332). Bio-economic farm models are therefore well suited for the integrated assessment of agri-environmental policies where economic and environmental impacts often depend on farm characteristics and require a detailed description of farming activities. Farm models can be coupled with bio-physical models to capture bio-physical relations with high detail and to better reflect location factors such as climate and soil.

We couple a bio-economic farm model and a crop model to assess the economic and environmental impact of the revised implementation of the Nitrates Directive in Germany (European Council 1991), laid out in the Fertilization Ordinance (FO) in 2017 (BMEL 2017a). The revision reflects infringement proceedings by the EU Commission after Germany failed to fulfill the targets of the directive by inter alia exceeding the concentration of 50 mg nitrate (NO_3^-) l^{-1} in groundwater bodies (BMU & BMELV 2012, pp. 27ff.) and insufficient actions by policymakers to reduce the load. As a multi-target policy, the revised FO includes measures that aim, besides at a reduction of NO_3^- leaching, at lower ammonia (NH_3) and phosphorus (P) losses and indirectly reduce nitrous oxide (N_2O) emissions. Therefore, it is linked to further environmental targets such those described in the EU Water Framework Directive (WFD) (European Parliament, European Council 2000) and the EU Directive on the Reduction of National Emissions of Certain Atmospheric Pollutants (European Parliament; European Council 2016).

The FO consists of numerous partly interlinked measures of which the most important are described in the following (Table 4.1, see Chapter 2 for a complete overview). In other EU member states, the same or similar measures are in place to implement the Nitrates Directive. Firstly, different nutrient application thresholds limit the use of chemical fertilizer and manure, such as the limitation of manure application to 170 kg nitrogen (N) ha^{-1}. Under the FO 2017, these thresholds become stricter. Secondly, the FO prohibits fertilizer application during periods in autumn and winter, when the risk of NO_3^- leaching is highest (Cameron *et al.* 2013, p. 151). Related to that, farms need minimum manure storage capacities that are measured in months. Under the FO 2017, the banning periods are prolonged, and the minimum manure storage capacity must be increased by farms with high stocking densities. Thirdly, the FO 2017 bans manure application techniques linked to high NH_3 volatilization. While broadcast spreaders were still generally permitted under the FO

2007, they are now only allowed on bare land followed by immediate incorporation into the soil under the FO 2017.

Table 4.1 Key measures of the Fertilization Ordinance 2007 and 2017

Measure	Fertilization Ordinance 2007	Fertilization Ordinance 2017
Fertilizing planning	Unspecified and non-binding fertilizing planning	Clearly defined and compulsory fertilizing planning
Organic N application threshold	170 kg N $ha^{-1}a^{-1}$ N from animal sources	170 kg N $ha^{-1}a^{-1}$ N from animal and plant sources (biogas digestate from plant origin); lowering of accountable loss factors
Nutrient surplus thresholds	60 kg N $ha^{-1}a^{-1}$ 20 kg P_2O_5 $ha^{-1}a^{-1}$	50 kg N $ha^{-1}a^{-1}$ 10 kg P_2O_5 $ha^{-1}a^{-1}$; 0 kg P_2O_5 $ha^{-1}a^{-1}$ on P-enriched soils[c]
Banning periods – fixed	Grassland 15.11-31.1 Arable land 1.11-31.1	Grassland 1.11-31.1 Arable land 1.10-31.1
Banning periods – after harvest of the main crop	Organic nutrient application restricted to 40 kg ammonia N or 80 kg total N for catch crops, winter crops, and straw rotting[a]	Total nutrient application restricted to 30 kg ammonia N and 60 kg total N for catch crops, winter rapeseed, field forage and winter barley following cereals in crop rotation
Manure application techniques	Broadcast spreader allowed	Broadcast spreader banned except on bare land followed by prompt incorporation (after a transition period)
Manure incorporation on bare land	Required but no specification of exact time	Required within 4 hours
Minimum manure storage capacity	6 months[b]	6 months, 9 months for farms >3 livestock units ha^{-1}

Source: own summary based on BMELV 2007 and BMEL 2017a; [a] In the federal state of North Rhine-Westphalia, there was an additional restriction for fertilizer application after the harvest of the main crop. Fertilizer application was forbidden to (1) winter wheat following maize, winter rapeseed, potatoes, sugar beet, vegetables, and legumes, (2) cereals following silage maize, and (3) catch crops following maize and sugar beet; [b] defined at state level and no part of FO 2007; [c] according to the FO, >0.0002% P_2O_5 in soil applying the calcium-acetate-lactate method; N - nitrogen; P_2O_5 - phosphate; P - phosphorus

Calculations at the sectoral level indicate high costs for farmers to comply with the FO 2017 (Karl & Noleppa 2017, pp. 10ff.; BMEL 2017b, pp. 70ff.), while first estimates at farm-scale show a high variance in compliance costs (Chapter 5). An integrated assessment of the FO, which considers farm heterogeneity, assesses costs and potential improvement in the environmental status, is still missing. By coupling a bio-economic farm model and a field-scale cropping system model, we can fill this gap. The economic farm model simulates cost-minimal adaption of farmers to the new FO, considering relations between detailed fertilizer management options and yields simulated with the crop model. This allows quantifying the effects on yields and NO_3^- leaching, taking the impacts on climate and soil into account.

In the existing research, farm and crop modelling are linked if the analysis requires a precise representation of cropping activities and related externalities, such as assessments of climate change impacts (Gülzari *et al.* 2017; Purola *et al.* 2018) or agri-environmental programs (Schönhart *et al.* 2011). In the context of the Nitrates Directive, Belhouchette *et al.* (2011) use such a framework to assess the economic and environmental impact on arable farms in southwest France. The directive, introducing more efficient N management in cropping activities, is assumed to cause transaction costs of 5% of total costs. Non-compliance is possible and penalized with a premium cut of 3%. Results of this study find only slight changes in NO_3^- leaching and no large impact on farm income. However, results for NO_3^- leaching differ for the assessed farm types depending on the extent of compliance and the change of grown crop shares, which is caused by the measure.

With this background, the contribution of this chapter is twofold. Firstly, we develop and present a generic modelling setup based on the connection between the bio-economic farm model FarmDyn and a specific configuration of the crop system modelling framework SIMPLACE. Secondly, we use that setup for an integrated assessment of the impacts of the 2017 revision of the FO, the implementation of the Nitrates Directive in Germany. We focus on specialized pig fattening farms and arable farms in the German federal state of North Rhine-Westphalia (NRW). Pig fattening farms are selected as they are strongly affected by the revision (Chapter 5). NRW is chosen as it is characterized by intensive, regionally concentrated livestock production (LWK NRW 2018b, p. 24) and holds 29% of the German fatteners stock (Destatis 2017, p. 19). As the export of excess manure from livestock to arable farms is a major compliance strategy, increased use of manure on arable farms is expected. To capture the effect, we also assess the impact on arable farms not currently using manure who are likely to import manure under the FO 2017.

4.2 Material and methods

4.2.1 FarmDyn

FarmDyn is a generic bio-economic farm-level model, which has been used for various applications (e.g. Budde 2013; Lengers *et al.* 2014; Schäfer *et al.* 2017). In the following paragraphs, we describe the scenario set up for the study at hand, the implementation of the measures of the FO, and corresponding compliance strategies. For further details, the reader can refer to a complete model documentation available online, which also covers technical aspects of the model connection (Britz *et al.* 2018). Relevant input-output coefficients are summarized in Appendix 4.B.

General description and modelling set up

FarmDyn is based on mixed-integer linear programming. It assumes a fully informed and rational decision maker maximizing farm profit by optimal choice of crop, fertilizer, manure, herd, and feed management based on a detailed representation of bio-physical and economic processes of different farming systems. FarmDyn relies on planning data, official statistics, and expert knowledge.

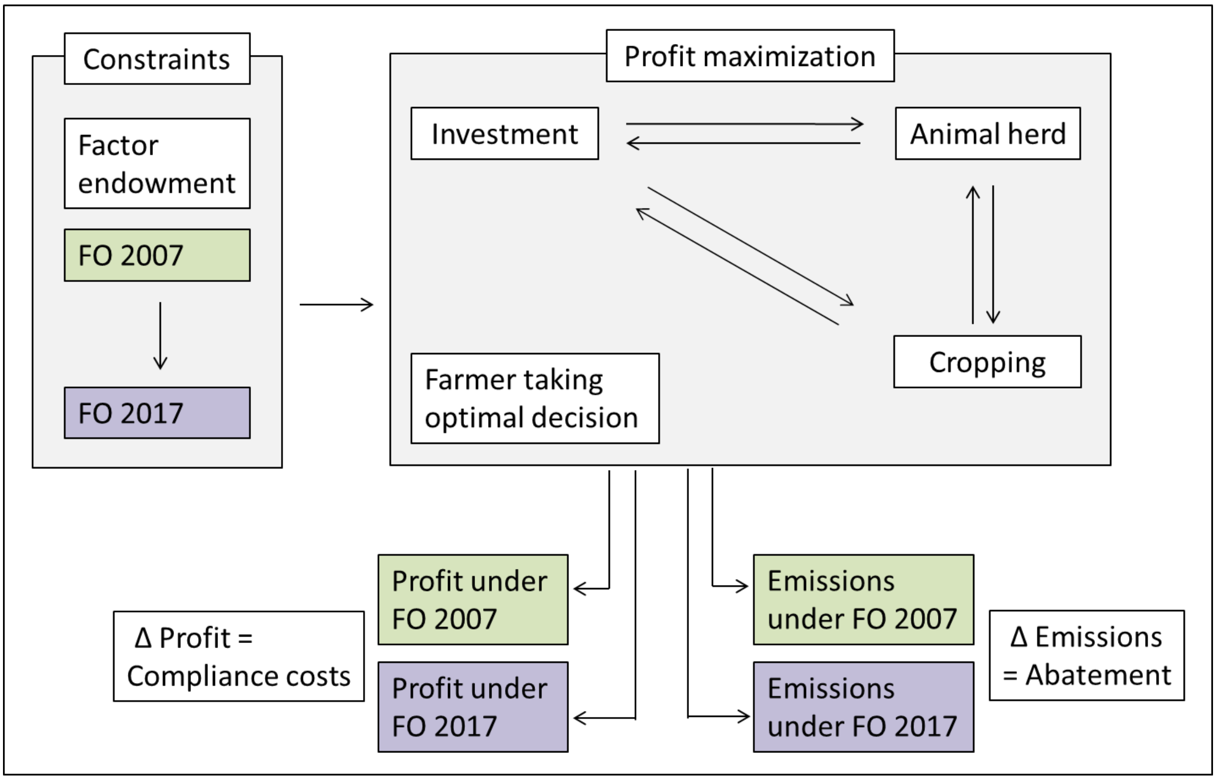

Figure 4.1. Estimation of the on-farm compliance costs and emission changes induced by the Fertilization Ordinance 2017 in FarmDyn

Source: own illustration; FO - Fertilization Ordinance

For this study, FarmDyn is applied in a comparative-static setting. For assessing adjustments to the new FO 2017, the model is run both for the legislative framework of the FO 2007 and 2017, respectively (Figure 4.1). Changes in economic farm performance and emissions between these two runs allow calculating compliance costs as well as emission reductions of different forms of reactive N. To capture the observed farm types (Section 4.2.5), farm size, P soil status, and crop rotations are exogenously set to the same values in both runs. We apply a sunk costs approach to calibrate FarmDyn on the observed herd size and thus stocking density under the FO 2007 by providing each farm with exactly the necessary stable places and machinery. The related investment costs are considered sunk such that the farmer fully uses the existing stable under the FO 2007 as only variable stable costs enter the optimization process.

Measures of the FO and compliance strategies

Under the FO 2017 and 2007, there are four different nutrient application thresholds, which limit the application of manure and partly of chemical fertilizer. First, the application of manure N after stable and storage losses is restricted to 170 kg N ha^{-1} on farm average, an unchanged threshold directly prescribed by the Nitrates Directive. However, the accounted share of standard NH_3 losses for stable and storage losses from pig manure is reduced from 30% in the FO 2007 to 20% in the FO 2017, implying lower allowed manure N application from a given pig herd. Farms can comply by lowering stocking density, changing feeding patterns, and exporting manure (Table 4.2). Both smaller herds and N-P reduced feeding management lower accounted N excretions. In line with the FO, we distinguish between N-P reduced and strongly N-P reduced feeding patterns; corresponding nutrient excretion is provided by the FO 2017. We consider the nutrient composition of these feeding regimes (DLG 2014, p. 71) as well as corresponding feed compositions (Stalljohann 2017, pp. 18ff.) in addition to the constraints in the pig feeding module of FarmDyn. Manure export from the farm, linked to costs of 12 € m^{-3} (Appendix 5.G), lowers the amount of manure N applied on the farm.

Farms face N and phosphate (P_2O_5) surplus restrictions as two further thresholds, calculated from nutrient input via manure and chemical fertilizer minus removal by harvested products. The maximal surpluses, in a sliding multi-year average, are lowered under the FO 2017 from 60 to 50 kg N ha^{-1} and 20 to 10 or even 0 kg P_2O_5 ha^{-1}. The zero P_2O_5 surplus threshold applies to soils with high P status. In addition to the compliance strategies mentioned above, farms can adapt by selling crop residues to increase nutrient removal. We consider selling straw from cereal production, whereas all other residues stay on the field. Drawing on LWK Nds. (2018a), costs for recovering, storage, and nutrient removal with straw are assumed to be 75 € t^{-1}, while possible impacts on the N pool and yield effects are reflected in the crop model simulations (Section 4.2.2). Observed German straw prices are between 70 and 190 € t^{-1} (KTBL 2016, p. 265), i.e. on average far above costs of exports. Expert judgment suggests that only around one-third of the cereal straw is currently sold in NRW (LWK NRW 2018b, p. 22), letting us chose the lowest reported straw price of 70 € t^{-1}. Reduced N fertilization intensity is another adaption measure to stricter N nutrient surplus limits. It increases the share of N taken up by the crop, thus reduces the N surplus and potential losses to the environment. However, it lowers the yield depending on the current levels of N inputs and crop yields. This is reflected in the different fertilization scenarios and corresponding crop model results (Section 4.2.2). Due to profit-maximizing behavior, FarmDyn chooses the fertilizing intensity such that the economic return from the yield response to a change in fertilization equals its marginal costs. However, N surplus thresholds restrict that choice and might require reduced N input and thus lower yields.

Table 4.2 Overview of measures of the Fertilization Ordinance and corresponding compliance strategies in FarmDyn

	Fertilizing planning	Organic N application threshold	N surplus threshold	P_2O_5 surplus threshold	Banning periods for manure application	Manure application techniques requirements	Manure storage capacity requirements
Reduced stocking density	X	X	X	X	X	X	X
Manure export	X	X	X	X	X	X	
Changed feeding	X	X	X	X			
Increased nutrient removal (e.g. straw)	X		X	X			
Reduced fertilizing intensity	X		X	X			
Catch crops					X		
Investment into manure storage					X		X
Investment into low-emission application techniques						X	

Sources: own illustration; N - nitrogen; P_2O_5 - phosphate

The fourth application threshold in the FO 2017 reflects the renewed and mandatory fertilizing planning and acts as a fertilization quota at the farm-level. The fertilizing planning is mainly relevant for N as it is not elaborated for P_2O_5 and does not differ from the P_2O_5 surplus calculation. Depending on the yield level, a crop specific N application limit is defined taking into account soil mineral N content in spring and carry-over effects of previous crops. The derived N application rate as the outcome of the fertilizing planning must not be exceeded by the sum of N from chemical fertilizer and manure N. The latter is accounted with prescribed mineral fertilizer equivalents (MFE), which reflect the amount of chemical fertilizer replaced by manure nutrients. We use the officially published average soil mineral N contents (LWK NRW 2018a, p. 1), which farmers are allowed to use in their fertilizing planning calculations instead of on-farm measurements. All other parameters are defined by the FO. To comply with the obligatory fertilizing planning, the same compliance strategies as with regard to the surplus restrictions are relevant.

The $N:P_2O_5$ ratio required by the prevalent crops relative to the $N:P_2O_5$ ratio in the excreted manure is a key attribute deciding which of the four described thresholds becomes most binding for manure application. The N content of the manure applied in the field is influenced by the amount of N losses on the farm. The N loss factors accounted in the different thresholds, however, are constant standard loss factors. Therefore, the described thresholds should be understood as legally defined nutrient loss indicators, while the actual losses and manure N content might differ. We use an N flow approach in FarmDyn for a detailed emission accounting (Section 4.2.4).

Besides the application thresholds, stricter banning periods for manure application apply in the FO 2017, especially now being more restrictive for manure application in autumn after the harvest of the main crop. However, an additional regulation in NRW included tighter limitations of manure application in autumn already under the FO 2007 (Table 4.1). In response to stricter banning periods, farms can export manure, reduce stocking density and invest into additional manure storage capacity. In addition, the growing of catch crops in autumn as pre-crop for main crops sown in spring allows higher manure application. In FarmDyn, mustard can be grown as a catch crop, which is also reflected in the SIMPLACE simulations (Section 4.2.2). However, the possibility to grow catch crops as well as the need to adapt to stricter manure banning periods depends on the type of crop rotation, especially on the proportion of spring crops. Besides the banning periods, agronomic constraints restrict the time when manure application is possible in the respective crops.

In order to ensure that farms can bridge the banning periods, minimal manure storage capacities are prescribed. Under the FO 2017, farms exceeding 3 livestock units (LU) ha^{-1} need to increase their manure storage capacity from 6 to 9 months. To comply with this measure, farms can reduce stocking density or invest in additional manure storage capacity. Annualized costs for manure storage range from 1.82 to 6.63 € m^{-3} (KTBL 2016, p. 153), reflecting economies of scale.

Finally, the FO defines the legally allowed manure application techniques. Under the FO 2017, broadcast spreading is banned after a transition period except for application on bare land followed by incorporation within 4 hours. Otherwise, low-emission manure application techniques are required. In order to comply, farmers can hence either increase the share of manure applied on bare land followed by direct incorporation or use the more costly application technique. We assume that the trailing hose technique is used and provided by a contractor. Application costs are 1.74 € m^{-3} for broadcast spreading and 2.80 € m^{-3} for trailing hose application (Kuratorium für Betriebshilfsdienste und Maschinenringe in Westfalen-Lippe e.V. 2017, p. 6; KTBL 2018a). We do not consider additional costs for the manure incorporation required within 4 hours.

4.2.2 SIMPLACE

To provide yields and nutrient losses under varying fertilizer management to FarmDyn for selected crop rotations and locations, we use the modular crop system modelling framework SIMPLACE (Scientific Impact assessment and Modelling Platform for Advanced Crop and Ecosystem management). For this study, it combines the components LINTUL5, NPKdemandSlimN, SlimRoots, SlimWater and SoilCN as a specific model configuration (for a detailed documentation, refer to Gaiser *et al.* (2018)). LINTUL5 is the core crop growth component, widely used in various studies at the field, country, and continental scale (Zhao *et al.* 2015; Gaiser *et al.* 2013; Hoffmann *et al.* 2016). It simulates crop growth rates (limited by solar radiation only) under water and nutrient limited conditions, in the absence of pests, diseases, and weeds (Wolf 2012). Biomass production is based on intercepted radiation according to Lambert-Beer's law and light use efficiency. Partitioning coefficients, defined as a function of the development stage of the crop, distribute the biomass among various crop organs (leaves, stems, storage organs and roots).

In the SIMPLACE configuration used in this study, total crop growth, root-shoot partitioning, and leaf area expansion are further influenced by water stress, simulated jointly by SlimWater and SlimRoots. SlimWater is a conceptual tipping bucket soil water balance model, which subdivides the soil in a variable number of layers and substitutes the two-layer approach in LINTUL5 (Addiscott & Whitmore 1991). SlimRoots contributes vertical root extension rate as well as root length density in each soil layer. To estimate N uptake by the crop, turnover in the soil, and leaching of soil mineral N (NO_3^--N and ammonium-N) in layered soils, we use the sub-models NPKDemandSlimN (a modified version of the SLIM model (Addiscott & Whitmore 1991) and SoilCN (Corbeels *et al.* 2005)). The model configuration and its derivates have been tested under various climate, soil and management (Srivastava *et al.* 2019; Maharjan *et al.* 2019; Webber *et al.* 2018; Durand *et al.* 2018; Coucheney *et al.* 2018; Grosz *et al.* 2017; Webber *et al.* 2015) and compared to other cropping systems models within the model intercomparison projects AgMIP and MACSUR (Kollas *et al.* 2015; Yin *et al.* 2017). The code for SIMPLACE and the described model components can be assessed in the model documentation (Enders & Krauss 2019).

Dataset

Daily climate time series for the period 1999 to 2008 at 1 km resolution cover minimum and maximum air temperature, precipitation, global solar radiation, wind speed, and relative humidity. They are interpolated from measured climate variables provided by the German

Meteorological Services (DWD) and joined at the same resolution with soil data, based on combinations of soil types at the scale of 1:50,000 (Geological Service NRW n.d.) and related physical parameters (Angulo *et al.* 2014; Federal Institute for Geosciences and Natural Resources in cooperation with the Federal Geological Services 2005). Further soil parameters are obtained as follows: 1) Organic carbon (C) and C:N-ratio of soil layers are approximated using pedotransfer functions (Angulo *et al.* 2014; Geological Service NRW n.d.). 2) Top soil layer C:N – ratio was set to 10. 3) Gravel content corrected bulk density are approximated following Poesen & Lavee (1994) and Torri *et al.* (1994).

Model calibration at district level uses the full information on climate and soil properties at the 1 km resolution. Crop yields for the calibration period 2000 to 2008 are obtained from the statistical office of North-Rhine Westphalia (IT.NRW n.d.), complemented by typical management practices for the study regions in the respective time period from a farm planning handbook (KTBL 2006).

Crop yields are simulated in farm type dependent typical crop rotations in the regions 141 (“Jülicher Börde”), 142 (“Niederrhein und südliches Münsterland”) and 148 (“Südliches Weser-Ems-Gebiet”), derived from observed farm type specific crop shares and expert knowledge (Table 4.4). 108 different fertilizer scenarios are established and applied to the crop rotations defined in each region which reflect 1) different chemical fertilizer and manure application rates and their timing, 2) with and without catch crops and, 3) with and without straw removal. As an example, Appendix 4.C illustrates the considered combinations of chemical fertilizer and manure for silage maize and winter wheat. Due to computing restrictions, the simulations of the 108 fertilizer scenarios are only performed for three grid cells in each region, representing the three most dominant cropland soils.

Model calibration and evaluation

The calibration at 1 km resolution grid cells uses one typical sowing and harvest date for each crop (winter wheat, silage maize, maize for corn-cob mix, sugar beet, winter barley, winter rapeseed) in the 3 Soil-Climate-Regions (SCRs). Details about creating the crop parameter file used in the simulations and the metrics used to assess model accuracy during calibration are given in Appendix 4.D.

Simulated mean crop yields and N in storage organs fit well (Appendix 4.E, Appendix 4.F) in all three SCRs under the assumed water and nutrient-limited conditions. The Mean Relative Error (MR) varies from maximum 1.5% to -1.8% for crop yields and from 1.7% to -5.8% for N in storage organs, depending upon the crop and the region. Though, the Mean Residual Error (ME) varies from maximum 206.1 kg ha^{-1} to -213.2 kg ha^{-1} in crop yields and 3.0 kg ha^{-1} to -6.3 kg ha^{-1} for N in storage organs.

4.2.3 Model connection

We apply a loose model connection to couple FarmDyn and SIMPLACE, i.e. there is no connection at runtime. SIMPLACE provides crop yields and NO_3^- leaching rates for cropping activities, differentiated combinations of chemical fertilizer and manure use, scenarios with or without straw removal and catch crops (Figure 4.2). FarmDyn selects from these the profit-maximizing ones under resource and regulatory constraints such as the FO. Following Janssen *et al.* (2011, pp. 149ff.), a loose model connection requires a conceptual integration, which here relates mostly to different temporal dimensions, as other dimensions (crop rotations, location of selected farm, farm management) are already harmonized during data construction. SIMPLACE follows daily time steps over numerous years whereas FarmDyn works mostly with a monthly resolution for an average year. The necessary averaging is provided by the in-built aggregator function of the SIMPLACE framework, while management and soil conditions stay constant over the simulation period.

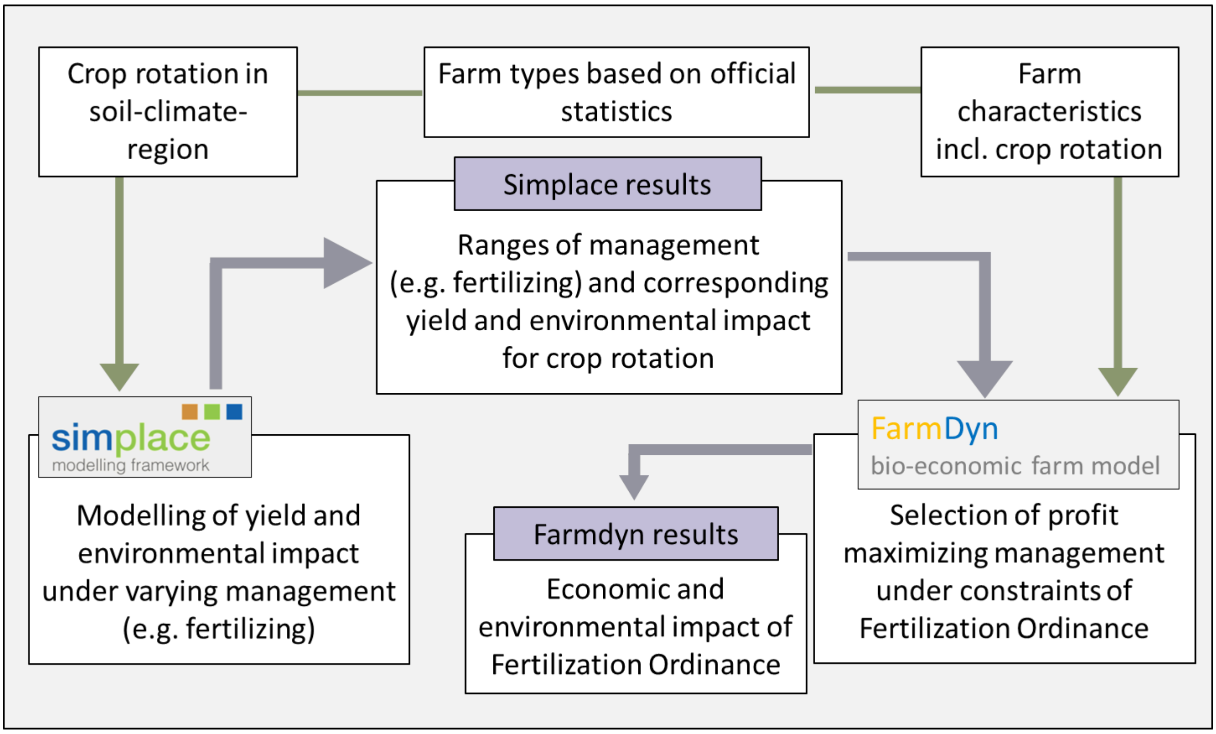

Figure 4.2. Overview of the model connection

Source: own illustration

4.2.4 Economic and environmental indicators

To assess the environmental and economic impact of the FO revision, different environmental and economic indicators are calculated at farm-scale. Emissions from down- and upstream sources related to input production or output use are not included. The environmental indicators relate to different forms of reactive N as the main target emissions of the FO.

Nitrous oxide, nitrogen oxide, and ammonia losses

Nitric oxide (NO), dinitrogen (N_2), N_2O and NH_3 emissions are calculated in FarmDyn following an N flow approach. N losses are quantified at the stable, storage and application stage. Reactive N emitted on one stage cannot enter the next one which requires also quantifying N_2 emissions. Related emission factors (EF) are identical to the ones applied in the calculation of the National Inventory Report on the German Greenhouse Gas Inventory and the Informative Inventory Report on the German Emissions of Air Pollutants (Haenel *et al.* 2018), summarized in Table 4.3. NH_3 volatilization following manure application depends on the manure application technique and the speed of manure incorporation following the application on bare land. EF reach from 0.06 kg NH_3-N (kg total ammonia nitrogen (TAN))$^{-1}$ for trailing hose application with incorporation within 4 hours to 0.25 kg NH_3-N (kg TAN)$^{-1}$ for broadcast spreading without incorporation (Appendix 4.A). At every step of the N flow, indirect N_2O emissions are calculated for NO-N and NH_3-N, being 0.01 kg N_2O-N (kg N)$^{-1}$. NO_3^- leaching is linked to 0.0075 kg (kg N)$^{-1}$ of indirect N_2O-N emissions (IPCC 2006a, p. 11.24). The latter occur when part of the NO_3^- is transformed to N_2O in nitrification and denitrification processes. We report emissions as kg N in the compound to facilitate the comparison with N loss indicators of the FO.

Table 4.3 Emission factors for ammonia, nitrous oxide, nitrogen oxides and dinitrogen related to total nitrogen and ammonia nitrogen

	NH_3	N_2O-N kg (kg N)$^{-1}$	NO-N kg (kg N)$^{-1}$	N_2-N kg (kg N)$^{-1}$
Stable	0.3 kg NH_3-N (kg TAN)$^{-1}$ [a]	0.005 [e]	0.1*0.005 [g]	3*0.005 [i]
Storage	0.105 kg NH_3-N (kg TAN)$^{-1}$ [b]			
Manure Application	0.06-0.25 kg NH_3-N (kg TAN)$^{-1}$ [c]	0.01 [f]	0.012 [h]	-
Chemical fertilizer application	0.01 kg NH_3 (kg N)$^{-1}$ [d]	0.01 [f]	0.012 [h]	-

[a] Dämmgen et al. (2010, p. 245); [b] Estimation from Haenel et al. (2018, p. 187) based on Döhler et al. (2002, pp. 62f.); [c] Appendix 4.A; [d] EEA 2016 (p.17), [e] IPCC (2006b, p. 10.62); [f] IPCC (2006a, p. 11.11); [g] 10% of the N_2O emissions according to Haenel et al. (2012, pp. 78f.); [h] Estimation from Haenel et al. (2018, p. 326) based on Stehfest & Bouwman (2006); [i] 300% of the N_2O emissions according to Jarvis & Pain (1994, p. 32); N_2 - dinitrogen; N_2O - nitrous oxide; N - nitrogen; NH_3 - ammonia; NO - nitric oxide; TAN - total ammonia nitrogen

Nitrate leaching

For the simulation of percolation of water and NO_3^- leaching in SIMPLACE, the soil profile at each location is technically sub-divided into soil layers with a thickness of 3 cm. The sub-model NPKDemandSlimN, which is adapted from the SLIM model (Addiscott & Whitmore 1991), calculates the daily NO_3^- fluxes in each soil layer based on the water fluxes and the total NO_3^- concentration. The necessary water fluxes are provided by water balance component SlimWater, which only considers vertical flows. Thus, the NO_3^- flux from a soil layer occurs only into the soil layer directly below. In a first step, the balance of the daily fluxes in each layer (inflow from the soil layer above and outflow to the soil layer below) provides the new NO_3^- contents in each soil layer. In a second step, the remaining NO_3^- is then distributed to the fractions of retained water and to the mobile water fraction. In the deepest soil layer, the downward NO_3^- flux corresponds to the leached NO_3^-. The sub-model also calculates daily crop N uptake based on the daily crop N demand and on the available soil mineral N (NO_3^--N and ammonium-N) in the rooted soil layers.

Compliance costs

We calculate compliance costs with the FO 2017 as the economic indicator, i.e. costs related to fulfill optional or compulsory measures in regulations (Uthes *et al.* 2010, p. 287; Mack & Huber 2017, pp. 35f.). They are hence not directly linked to emission reductions and thus different from (marginal) abatement costs, which quantify costs associated with an (additional) emission decrease. In FarmDyn, compliance costs are calculated as the difference of the economic performance under the FO 2007 and 2017, reflecting revenues from sold outputs minus costs for inputs and new investments. Investments into existing stables and machinery are not accounted for due to the sunk cost approach, which reproduces the observed animal stock (Section 4.2.1). We assume that land is farm owned and work performed by family labor. As indicated above, manure spreading is assumed to be provided by a contractor.

Arable farms may increase their farm income if they start importing manure, which saves costly chemical fertilizer. They can hence exhibit ‘negative compliance costs’ from costs saving and revenue increases. For arable farms, costs or costs savings are related to the area in ha. Compliance costs for pig fattening farms are expressed per number of slaughtered heads under the FO 2007. This allows capturing the economic impact of a reduced stocking density as a compliance strategy with the FO 2017. The chosen references facilitate comparison to other studies and published standard gross margins.

4.2.5 Farm types

To account for farm heterogeneity, we select three pig fattening and three specialized arable farm types from a farm typology for NRW (Chapter 3, Table 4.4). Largely based on data from the German Farm Structure Survey (FSS) 2016, which covers all German farms above a defined size threshold, this typology groups farms according to specialization, size in ha and stocking density. It reports for each group relevant farm characteristics such as the area of different crops, animal stock, and farm location. That allows evaluating the relative importance of farm types in NRW regarding farm numbers, animal stock, and area and provides core farm characteristics for model initialization and parametrization.

We selected two pig fattening farms that represent groups with the biggest share of the pig stock in NRW. However, we excluded land-free pig farms from the selection that are often part of a bigger farming unit (see the discussion in Section 4.4.2). In addition to the two most frequent groups, we chose the fifth most frequent pig farm type in NRW, which exceeds 3 LU ha^{-1} and is most affected by the revision. All pig farm types are assumed to have highly P-enriched soils, an assumption supported both by single farm and regional data (Osterburg & Techen 2012, p. 201; LWK NRW 2018b, p. 50). The pig farm type PIG-EX is assumed to already apply low-emission manure application techniques under the FO 2007, as there is a positive correlation with farm size in ha and a negative correlation with stocking density for the use of these techniques (Appendix 5.C). All pig farm types have at the benchmark a manure storage capacity of 6 months as this is the minimum capacity prescribed under the FO 2007.

The arable farms ARAB-SB and ARAB-WR are the most dominant arable farm types with regard to the land area covered in the SCRs 141 and 142. These regions are chosen as they will likely face an increased manure import under the FO 2017. They already import high amounts of manure under the FO 2007 and are close to the livestock intensive regions (LWK NRW 2018b, pp. 15, 37). The maximum manure import is exogenously defined under the FO 2017, assuming 20 m^3 ha^{-1} for farm type ARAB-SB and 15 m^3 ha^{-1} for farm-type ARAB-WR. Farm type ARAB-SB grows winter cereals and sugar beets, while ARAB-WR crops winter cereals and winter rapeseed. Manure use is more restricted for ARAB-WR due to high minimum chemical fertilizer need and the limited time windows for manure application in winter crops. Usually, the contracts between manure exporting livestock farms and manure importing arable farms stipulate free delivery to the field while the application costs rest with the importing farm; we distribute costs accordingly. Furthermore, manure is assumed to be directly applied after delivery and, hence, there is no manure storage necessary on importing arable farm types. The manure importing farm has to pay the expenses for manure application. The arable farm type ARAB-noMAN continues to solely use chemical fertilizer. It is the most frequent arable farm type with regard to the land area covered in whole NRW.

Table 4.4 Selected farm types and their characteristics

	Arable farm type with sugar beet (ARAB-SB)	Arable farm type with winter rapeseed (ARAB-WR)	Arable farm type without manure import (ARAB-noMAN)	Extensive pig fattening farm type (PIG-EX)	Medium intensive pig fattening farm type (PIG-MED)	Intensive pig fattening farm type (PIG-INT)
Farm Size [ha][a]	69.95	66.70	16.91	74.64	62.97	33.28
Stocking Density [LU ha^{-1}][a]	-	-	-	1.7	2.3	3.4
Representations of land area [%][a]	1.38	2.90	3.80	-[b]	-[b]	0.37
Representation of farms [%][a]	0.83	1.78	8.09	1.26	0.96	0.47
Representation of pig stock [%][a]	0	0.02	0.01	8.99	8.63	3.50
Soil-climate region[a]	141	142	142	142	148	148
Crop rotation[a]	WW-WW-SB	WW-WB-WR	WW-WB-WR	WW-WB-CCM	WW-WB-CCM-CCM	WW-WB-CCM-CCM
Manure application technique under FO 2007	-	-	-	Trailing hose	Broadcast	Broadcast
Manure storage capacity under FO 2007 [months]	-	-	-	6	6	6
P soil status	Balanced P status	Balanced P status	Balanced P status	High P status	High P status	High P status
Manure import under the FO 2017	20 m^3	15 m^3	-	-	-	-

[a] based on the typology from Chapter 3; [b] Values are not available due to privacy protection regulations (see also Section 3.2.1); CCM - maize for corn-cob-mix; FO - Fertilization Ordinance; LU - livestock units; P - phosphorus; SB - sugar beet; WB - winter barley; WR - winter rapeseed; WW - winter wheat

Based on information on farm location in the FSS, the farm types are assigned to SCRs (Roßberg *et al.* 2007) as the regions reflected in the soil and climate conditions underlying the SIMPLACE runs (Section 4.2.2). This allows a consistent representation of soil and climate specific cropping activities. The assessed farm types are located in three of the nine SCRs in NRW (Figure 3.2). For the pig fattening farm types and the arable farm type ARAB-noMAN, we chose the SCRs that hold highest share of farms represented by the assessed farm type. For the two other arable farm types assumed to start importing manure, SCR 141 and 142 are chosen as these regions will likely increase manure imports. For every farm type in the selected SCRs, a typical crop rotation is defined based on the crop shares derived from the FSS 2016 and expert judgement by Gaiser (2018).

4.3 Results

4.3.1 Arable farm types

The effect of the manure import under the FO is differently assessed for the arable farm types ARAB-SB and ARAB-WR. For the farm type ARAB-SB, an additional model run with FarmDyn is included to capture the adaption to the FO 2017 without manure import. For the ARAB-WR, this is not needed as ARAB-noMAN reflects this situation as both farms are located in the same SCR and cultivate the identical crop rotation.

Arable farm type with sugar beet (ARAB-SB)

The arable farm type with sugar beet, ARAB-SB, is found in SCR 141 and grows the crop rotation winter wheat, winter barley, and sugar beet. Under the FO 2007, the farm type does not reach any nutrient application threshold. However, the farm type exceeds the N quota by 1,085.96 kg N (Table 4.5), which is not binding under the FO 2007.

To comply with the N quota under the FO 2017, ARAB-SB lowers its average chemical N fertilizer applications from 169.36 to 151.93 kg N ha^{-1}, which slightly decreases average yields by 0.13 t ha^{-1} for winter wheat and by 1.16 t ha^{-1} for sugar beet. Related compliance costs are small (4.74 € ha^{-1}). This illustrates that the farm type operates at the economic optimum where the returns from a marginal yield increase equal the marginal costs for fertilizer. However, this implies relatively low N use efficiency: only a small share of the additional 17.43 kg N ha^{-1} applied under FO 2007 compared to FO 2017 ends up in the harvested product (2.57 kg N ha^{-1}). When not being incorporated into stable soil organic matter, the excess N applied as chemical fertilizer (14.86 kg N ha^{-1}) which was not taken up by the crop is therefore prone to leaching. Hence, the slight reduction in yields leads to a relatively large reduction of NO_3^- leaching, declining from 35.44 kg ha^{-1} to 23.55 kg NO_3^--N ha^{-1}. As the total N input is lowered, NH_3, NO, and N_2O emissions decrease likewise.

In the second model run, the farm type ARAB-SB is assumed to import up to 20 m^3 ha^{-1} of manure which substitute on average 90.49 and 59.02 kg of chemical N and P_2O_5 fertilizer, respectively. The P_2O_5 surplus increases from 0 to 8.62 kg ha^{-1} as P_2O_5 imported with the manure exceeds the crop demand at the current yield level. However, as arable farms often tend to suffer from P deficiency in the soil, this is rather a positive effect. The manure import is also linked to an increase in the legally reported N surplus from 30.06 to 41.39 kg N ha^{-1} compared to the FO 2007 without manure import. The change in the surplus reflects the fact that one kg of N in form of manure leads to a lower increase in crop yield than one kg N from chemical N fertilizer, but it is also caused by the changes in the surplus calculation scheme under the FO 2017. Still, the farm stays below the surplus threshold of 50 kg N ha^{-1}. Costs decrease by 108.00 € ha^{-1}. This reflects the saved costs for chemical fertilizer, down from 266.29 to 87.97 € ha^{-1}, which more than offset the additional cost of 56.00 € ha^{-1} for manure application. When compared to the arable farm without manure import under the FO 2017, NO_3^- leaching is increased with the import of manure, because, in total, more N is applied per ha (151.93 against 183.27 kg N ha^{-1}) with the same N removal by the crops as the yield level remains the same. Hence, the imported N as manure is less effective in increasing crop yields than the N in the chemical fertilizer and higher leaching loss occurs. Compared to the FO 2007, NO_3^- leaching still decreases (from 35.44 to 31.68 kg NO_3^--N ha^{-1}) for ARAB-SB because the increased N use efficiency due to a slightly reduced yield level overcompensates the NO_3^- leaching rise due to manure import. However, NH_3 emissions rise from 1.39 to 8.64 kg NH_3-N ha^{-1} because the volatilization from manure application is higher compared to chemical N fertilizer application. As total N input to the system increases, NO and N_2O emissions also slightly rise.

Arable farm type with winter rapeseed (ARAB-WR) and without manure import (ARAB-noMAN)

The arable farm type with winter rapeseed ARAB-WR and the farm type without manure import ARAB-noMAN are located in SCR 142 and are both growing the crop rotation winter wheat, winter barley, and winter rapeseed. The farm types are jointly described as they only differ by size and by manure import under the FO 2017 which takes only place for ARAB-WR. The analysis of ARAB-noMAN under the FO 2017 allows isolating the impact of the FO 2017 without manure import. Hence, an additional model run as for ARAB-SB is not necessary.

Under the FO 2007, both ARAB-noMAN and ARAB-WR do not reach any legal nutrient application thresholds. Related nutrient surpluses according to the FO 2007 amount to 19.20 kg N ha^{-1}. Emissions are 1.21 kg NH_3-N ha^{-1}, 1.77 kg NO-N ha^{-1}, 1.51 kg N_2O-N ha^{-1} and 40.22 kg NO_3^--N ha^{-1}. Under the FO 2007, NO_3^- leaching is slightly higher for ARAB-WR (40.2 kg NO_3^--N ha^{-1}) than for ARAB-SB (35.4 kg NO_3^--N ha^{-1}), although the N surplus on ARAB-WR farms is lower. This is firstly due to the fact that the remaining residues of winter rape in the farm type ARAB-WR, which are returned to the soil, contain more N compared to the sugar beet leaves in ARAB-SB. Secondly, in winter rape, there is a larger gap to the following crop (winter wheat) than in the case of sugar beets. Thus, the period for N decomposition and leaching is longer after the harvest of rape seed. In addition, the farm type ARAB-WR is located in the SCR 142, where the sandy textured subsoils with higher leaching rates are more frequent than in SCR 141 where the farm type ARAB-SB is found. In contrast to ARAB-SB, a lower intensity level of fertilizer use is profit maximizing for ARAB-noMAN and ARAB-WR such that the N fertilizer quota of the FO 2017 is not binding. Both farm types neither face compliance costs nor realize emission reductions under the FO 2017 without manure import.

ARAB_WR is assumed to import 15 m^3 ha^{-1} of manure under the FO 2017. This replaces 50.41 and 49.20 kg of chemical N and P_2O_5 fertilizer, respectively. The P_2O_5 surplus stays unchanged whereas the legally calculated N surplus increases from 19.20 to 41.41 kg N ha^{-1}. Again, this is caused by the revised calculation scheme under the FO 2017 and the higher total N input when replacing chemical fertilizer N with manure N. Applying the surplus calculation of the FO 2007, the N surplus only increases to 37.49 kg N ha^{-1}. ARAB_WR realizes a cost decrease of 97.41 € ha^{-1}. Costs for chemical fertilizer drop by 120.73 € ha^{-1} whereas additional costs for manure application only amount to 42.00 € ha^{-1}. Furthermore, the farm type increases fertilizing intensity and realizes slightly higher yields, which reflect the lower costs of N. The average winter rapeseed yield, for instance, rises from 2.99 to 3.02 t ha^{-1}. In line with ARAB-SB, the manure import leads to a slight increase of the average NO_3^- leaching rate from 40.22 to 45.68 kg NO_3^--N ha^{-1}. This is due to the higher amount of total N applied under FO 2017 (175.69 kg N ha^{-1}) compared to FO 2007 (147.8 kg N ha^{-1}), whereas N removal by the crops remains almost the same (128.6 against 130.4 kg N ha^{-1}). NH_3 emissions increase from 1.21 to 8.67 kg NH_3-N ha^{-1} because manure application is linked to higher volatile losses than chemical fertilizer application. N_2O and NO emissions mainly rise due to the increased total N input to the farming system by 27.89 kg N ha^{-1}.

Table 4.5 Economic and environmental indicators for arable farm types under the FO 2007 and FO 2017

		ARAB-SB			ARAB-WR		ARAB-noMAN	
		FO 2007	FO 2017 no manure	FO 2017	FO 2007	FO 2017	FO 2007	FO 2017
Thresholds of FO								
N Surplus[a, b]	kg ha^{-1}	30.06	15.19 (15.19)	41.39 (36.17)	19.20	41.41 (37.49)	19.20	19.20 (19.20)
P_2O_5 Surplus[b]	kg ha^{-1}	0	0	8.62	0	0	0	0
Organic N appl. threshold[b]	kg ha^{-1}	0	0	104.47	0	78.36	0	0
N Quota Ceiling	kg $farm^{-1}$	10761.11	10627.46	10632.71	10526.73	10596.82	2668.77	2668.77
N Quota Applied	kg $farm^{-1}$	11847.07	10627.46	10632.71	9858.09	10154.09	2499.26	2499.26
Farm management								
N removal with yield	kg ha^{-1}	139.31	136.74	136.73	128.6	130.42	128.6	128.6
Chemical N fertilizer	kg ha^{-1}	169.36	151.93	78.87	147.8	97.39	147.8	147.8
Chemical P_2O_5 fertilizer	kg ha^{-1}	59.02	57.93	0	56.93	7.73	56.93	56.93
Manure application	m^3 ha^{-1}	0	0	20	0	15	0	0
Manure trailing hose spread	m^3 $farm^{-1}$	0	0	1399	0	1000.5	0	0
Emissions								
NH_3-N emissions	kg ha^{-1}	1.39	1.25	8.64	1.21	8.67	1.21	1.21
NO-N emissions	kg ha^{-1}	2.03	1.82	2.2	1.77	2.11	1.77	1.77
N_2O-N emissions	kg ha^{-1}	1.73	1.55	1.94	1.51	1.87	1.51	1.51
NO_3^--N emissions	kg ha^{-1}	35.44	23.55	31.68	40.22	45.68	40.22	40.22
Cost savings	€ ha^{-1}		-4.74	108.00		97.41		

Source: own calcuation and illustration; [a] N surplus in brackets under FO 2017 is calculated according to the calculation scheme of the FO 2007; [b] Under the FO 2007, the following threshold were in place: N surplus of 60 kg ha^{-1}, P_2O_5 surplus of 50 kg ha^{-1}, organic N application threshold of 170 kg N ha^{-1}. Under the FO 2017, the N surplus is lowered to 50 kg ha^{-1} and the P_2O_5 surplus to 10 or 0 kg ha^{-1} depending on the P soils status; € - Euro; appl. - application; FO - Fertilization Ordinance; N_2O - nitrous oxide; N - nitrogen; NH_3 - ammonia; NO - nitric oxide; NO_3^- - nitrate; P_2O_5 - phosphate

4.3.2 Pig fattening farm types

Extensive pig fattening farm (PIG-EX)

The extensive pig fattening farm type PIG-EX does not reach any nutrient application thresholds under both the FO 2007 and 2017 (Table 4.6), reflecting the low stocking density of 1.7 LU ha^{-1}. As PIG-EX is assumed to already use the trailing hose technique under the FO 2007, also no changes in manure application are required. Accordingly, no change in management is observed. The available nutrients from manure alone would imply quite low crop yields such that the farm type applies additional chemical fertilizer input of 91.70 kg N ha^{-1} and 19.27 kg P_2O_5 ha^{-1} on farm average. Although there is no legal pressure to lower nutrient surpluses, the farm type still uses the strongly N-P reduced feeding strategy under both the FO 2007 and 2017, as feeding costs for the N-P reduced feeding strategy are slightly lower compared to alternatives. Under the FO 2017, the legal accounted N surplus and the organic N application threshold increase due to the changed calculation scheme.

The NO_3^- leaching is 33.40 kg NO_3^--N ha^{-1}. NH_3 emissions from manure stable, storage, and application are 38.07 kg NH_3-N ha^{-1}, whereas emissions from applications are only a minor share with 5.39 kg NH_3-N ha^{-1}. NH_3 losses are smaller compared to PIG-MED and PIG-INT under the FO 2007 as the farm uses already low-emission manure application techniques and the total excreted and applied N is less due to the low stocking density.

Medium intensive pig fattening farm (PIG-MED)

The medium intensive pig fattening farm type is characterized by a stocking density of 2.3 LU ha^{-1} and the absence of low-emission manure application techniques. Under the FO 2007, the farm type does not reach any nutrient application thresholds and is able to gap the banning periods with its existing storage capacity equivalent to 6 months of manure excretion. In line with PIG-EX, PIG-MED uses the strongly N-P reduced feeding strategy already under the FO 2007. PIG-MED shows NO_3^- leaching of 46.57 kg NO_3^--N ha^{-1} and NH_3 volatilization of 56.67 kg NH_3-N ha^{-1} under the FO 2007.

Under the FO 2017, the PIG-MED farm has to slightly lower its P_2O_5 surplus from 2.41 to 0 kg ha^{-1} and to use now low-emission manure application techniques. Furthermore, the amount of manure that can be applied after the harvest of the main crop decreases. This, however, is not linked to an adaption of the farming program as it is sufficient to apply manure to winter barley in autumn to gap the banning periods. The farm type faces moderate compliance costs of 0.42 € pig^{-1} mainly caused by the need to change the manure application technique. To lower its P_2O_5 surplus, the PIG-MED farms both sells straw on 4.49 ha to increase nutrient removal and exports with 0.54 m^3 ha^{-1} a small amount of manure. The

N surplus and the organic N application threshold increase due to the changed calculation scheme under the FO 2017. The calculation of the N surplus under the methodology of the FO 2007 shows that there is actually a surplus decrease. The use of the trailing hose technology for 65% of the applied manure increases the amount of N that becomes plant available due to lower NH_3 losses. It allows slightly decreasing the chemical N and, therefore, leads to a lower N surplus. The decrease from 79.88 to 77.00 kg ha^{-1} in chemical N lowers fertilizer costs from 102.21 to 98.99 € ha^{-1}. However, this does not compensate for the higher manure application costs of 13.61 € ha^{-1} in farm average or 0.32 € pig^{-1}.

Thus, the PIG-MED farm type requires only slight adaptions to comply with the FO 2017. Therefore, emission changes are close to zero. NO_3^- leaching decreases from 46.57 to 45.12 kg NO_3^--N ha^{-1}, because the rate of both manure and chemical N fertilizer slightly decreases as well as the N surplus according to the calculation scheme under FO 2007. Hence, the small reduction in chemical N use and the higher share of plant available manure N only slightly impact on NO_3^- losses. NH_3 losses from the application are considerably lowered from 12.83 to 8.70 kg NH_3-N ha^{-1}. However, the reduction of total NH_3 losses is only 7.32%, as NH_3 emissions mostly occur in the stable and during storage. Due to the lowered total N input, N_2O and NO losses also slightly decrease.

Intensive pig fattening farm type (PIG-INT)

The intensive pig fattening farm type is characterized by a high stocking density of 3.40 LU ha^{-1} and the absence of low-emission manure application techniques. Already under the FO 2007, the farm sells straw from 16.64 ha of winter cereals and exports 0.92 m^3 manure ha^{-1} to meet the P_2O_5 threshold of 20 kg ha^{-1}. Despite that surplus, it applies chemical P_2O_5 fertilizer as a starter fertilization for maize. As for PIG-EX and PIG-MED, the PIG-INT farm type already uses the strongly N-P reduced feeding strategy under the FO 2007. Furthermore, the farm type grows catch crops on 0.65 ha to be able to apply more manure in autumn as the available manure storage capacity is not fully sufficient to outlast banning periods. Compared to the other pig fattening farm types, the PIG-INT type shows higher losses under the FO 2007 with 50.16 kg NO_3^--N ha^{-1} and 81.73 kg NH_3-N ha^{-1}.

Under the FO 2017, the PIG-INT farm has to adapt to the zero P_2O_5 threshold, increase manure storage capacity and use low-emission manure application techniques. This implies compliance costs of 2.32 € pig^{-1}. To lower the P_2O_5 surplus from 20 to 0 kg ha^{-1}, the farm type exports additional 7.50 m^3 ha^{-1} of manure. This accounts for the largest share of the compliance costs with 1.41 € pig^{-1}. The P_2O_5 surplus under the FO 2007 reflects a low N: P_2O_5 relation in pig manure. Higher manure export under FO 2017 hence implies that N previous used for plant nutrition leaves the farm. This increases the chemical N use from 47.36 to 60.63 kg N ha^{-1}, driving fertilizer costs from 65.94 to 80.44 € ha^{-1}. The N surplus in accordance with the FO 2017 slightly increases due to the changed calculation scheme. However, following the old surplus calculation, there is a decrease from 29.13 to 4.11 kg N ha^{-1}. Under the FO 2017, the farm has to apply 342.79 m^3 of manure by trailing hose to fulfill the requirements regarding the use of low-emission manure application techniques. The remaining 437.33 m^3 can still be applied with broadcast spreader followed by instant incorporation. The farm type has 50% maize in the crop rotation which allows a high manure application on bare land in spring in contrast to the arable farm types which grow more winter crops. The PIG-INT farm type exceeds 3 LU ha^{-1} and therefore has to increase its manure storage capacity from 530 to 802 m^3. This is linked to annual costs of 0.85 € pig^{-1}. As there is now sufficient manure storage capacity to bridge the banning periods, the catch crop cultivation is no longer necessary under the FO 2017 and abandoned.

The farm type PIG-INT realizes major emissions reductions due to the FO 2017. NO_3^- leaching is reduced from 50.16 to 37.94 kg NO_3^--N. This can be explained by the strong reduction of the manure application which is equivalent to around 40 kg N ha^{-1}, whereas the N application with chemical fertilizer increases only by 13 kg N ha^{-1}. With similar levels of N removal by the crops, this leads to a strong reduction in the N surplus and therefore NO_3^- leaching. NH_3 volatilization from manure application is lowered from 17.53 to 8.48 kg NH_3-N due to the faster incorporation on bare land and the use of low-emission manure application techniques. However, as the major share of emissions occurs in the stable and manure storage, the total NH_3 emissions only decrease by 10.90%. The emission reduction is also realized by the increased export of the manure from the farm which may cause emission changes on the manure importing farm. The manure export and lower total applied N is also the major driver for the decrease of N_2O and NO losses. Interestingly, NO_3^- leaching under the FO 2017 is lower for the more intensive farm PIG-INT than for PIG-MED. The latter empties the manure storage before the banning periods by applying manure in autumn to winter barley which is linked to high losses. In contrast, the increased manure storage capacity of PIG-INT allows shifting all manure application to spring and causes lower NO_3^- leaching.

Table 4.6 Economic and environmental indicators for pig fattening farm types under the FO 2007 and FO 2017

		PIG-EX		PIG-MED		PIG-INT	
		FO 2007	FO 2017	FO 2007	FO 2017	FO 2007	FO 2017
Thresholds of FO							
N Surplus [a, b]	kg ha^{-1}	21.64 (21.64)	38.54 (21.64)	33.82 (33.82)	49.45 (26.59)	29.13 (29.13)	37.89 (4.11)
P_2O_5 Surplus [b]	kg ha^{-1}	0	0	2.41	0	20	0
Organic N appl. threshold [b]	kg ha^{-1}	78.83	90.09	106.64	119.22	153.03	138.71
N Quota Ceiling	kg $farm^{-1}$	11760.84	11760.84	10469.68	10474.05	5536.11	5565.54
N Quota Applied	kg $farm^{-1}$	10939.55	10939.55	9704.02	9405.3	5120.2	4694.79
Farm management							
N removal with yield	kg ha^{-1}	137.62	137.62	137.47	139.16	148.76	149.93
Chemical N fertilizer	kg ha^{-1}	91.7	91.7	79.88	77	47.36	60.36
Chemical P_2O_5 fertilizer	kg ha^{-1}	19.27	19.27	10	10	10	10
Manure application	m^3 ha^{-1}	15.94	15.94	21.56	21.02	30.93	23.44
Manure Broadcast spread	m^3 $farm^{-1}$	0	0	1357.5	457.31	1029.38	437.33
Manure trailing hose spread	m^3 $farm^{-1}$	1189.5	1189.5	0	866.23	0	342.79
Manure export	m^3 ha^{-1}	0	0	0	0.54	0.92	8.42
Manure storage capacity	m^3 $farm^{-1}$	595	595	679	679	530	802
Straw export	ha $farm^{-1}$	0	0	0	4.49	16.64	16.64
Catch crop cultivation	ha $farm^{-1}$	0	0	0	0	0.65	0
Stocking density	LU ha^{-1}	1.7	1.7	2.3	2.3	3.4	3.4
Emissions							
NH_3-N emissions	kg ha^{-1}	38.07	38.07	56.67	52.52	81.73	72.82
NO-N emissions	kg ha^{-1}	2.1	2.1	2.31	2.24	2.51	2.22
N_2O-N emissions	kg ha^{-1}	2.67	2.67	3.21	3.11	3.96	3.63
NO_3^--N emissions	kg ha^{-1}	33.40	33.40	46.57	45.12	50.16	37.94
Compliance costs	€ $fattner^{-1}$				0.42		2.32

Source: own calcuation and illustration; [a] N surplus in brackets under FO 2017 is calculated according to the calculation scheme of the FO 2007; [b] Under the FO 2007, the following threshold were in place: N surplus of 60 kg ha^{-1}, P_2O_5 surplus of 50 kg ha^{-1}, organic N application threshold of 170 kg N ha^{-1}. Under the FO 2017, the N surplus is lowered to 50 kg ha^{-1} and the P_2O_5 surplus to 10 or 0 kg ha^{-1} depending on the P soils status; € - Euro; appl. - application; FO - Fertilization Ordinance; LU - livestock units; N_2O - nitrous oxide; N - nitrogen; NH_3 - ammonia; NO - nitric oxide; NO_3^- - nitrate; P_2O_5 - phosphate

4.4 Discussion

4.4.1 Results

We estimated compliance costs with the FO 2017 for PIG-MED and PIG-INT of 0.42 € pig^{-1} and 2.32 € pig^{-1}, respectively. This lies within the range of 0 to 2.66 € pig^{-1} found in Chapter 5 for the pig farm population in NRW. Thus, PIG-INT falls in the group of pig farms with the highest compliance costs with the implementation of the FO 2017 for which manure export is identified as the main cost driver. The farm type PIG-MED is linked to the group of farms in the population which solely faces compliance costs due to the introduction of low-emission manure application techniques (Section 5.4). Differences between these cost estimations are mainly caused by differences in yield levels and crop N response, as well as assumptions about the costs of low-emission manure application techniques. The estimated compliance costs differ from findings by Karl & Noleppa (2017) and Menghi *et al.* (2015) due to differences in methodologies and the assessed measures (see Section 5.5.1 for a detailed comparison). Budde (2013, pp. 124ff.) assesses the impact of different water protection policies on the investment behavior of typical pig farms in NRW with a former version of FarmDyn, independent of the main model development. The author does not evaluate the FO 2017 but also finds strict measures regarding P_2O_5 as most limiting for manure application, impacting on farm-income but not preventing future investments to increase the animal stock. In our modelling approach, investment into additional stables is not possible and, hence, the economic results reflect a short-term view.

We do not report farm income as it highly depends on assumptions about land ownership, payments for labor and taxation choices. However, the calculation of compliance costs per pig and ha allows relating them to the standard gross margin which is "the balance between the standard value of production and the standard value of certain specific costs" (European Commission 1985, p. 2). In 2016/17, the standard gross margin per pig in NRW was 27.20 €, with major variable costs associated with feeding costs of 67.20 € pig^{-1} and piglets of 65.20 € pig^{-1} (KTBL 2018b). Hence, the compliance costs with the FO 2017 are small compared to other cost items. However, PIG-INT loses 8.53% of its standard gross margin. Furthermore, compliance costs may be higher as we do not assess all measures of the FO 2017, exclude transaction costs, and assume full compliance under the FO 2007 (Section 4.4.2).

The farm types ARAB-SB and ARAB-WR realize cost decreases of 108.00 and 97.41 € ha^{-1}, respectively, as per our assumption, they start to import manure. Our assumption reflects the increasing pressure on livestock farms to export manure under the FO 2017, which implies that other farms will import manure. The standard gross margin for the crops in the rotations found at the farm types ARAB-SB and ARAB-WR reaches from 516 € ha^{-1} for winter barley to 1,854 € ha^{-1} for sugar beet (KTBL 2018b). Hence, we find cost savings from manure import quite relevant compared with current gross margins, which also reflects our methodology (Section 4.4.3). The compliance costs due to the lower fertilization intensity, which we quantified as 4.74 € ha^{-1} for ARAB-SB, is negligible.

Belhouchette *et al.* (2011) report little income changes for arable farms without manure use in southwest France due to the implementation of the Nitrates Directive, which is in line with our findings. Generally, their results are difficult to compare with ours due to the differences in the assessed measures and assumptions of compliance with the regulation. NO_3^- leaching decreases by 6% for the farm type, which picks up alternative and more N efficient cropping activities (Belhouchette *et al.* 2011, p. 142). In our analysis, the compulsory fertilizing planning realizes a leaching reduction of 34% for ARAB-SB. In the analysis from Belhouchette *et al.* (2011, p. 136ff.), non-compliance is possible and activities in line with the directive are only implemented on a fraction of the farm land. At the field scale, however, the authors find a leaching reduction in the range of 2.5% and 50% from activities in line with the directive, which is in the range of our findings.

4.4.2 FarmDyn: Methodology and data sources

Following standard economic assumptions, the bio-economic farm model FarmDyn assumes a fully informed and rational decision maker maximizing farm profit. To comply with changing regulations such as the FO, farm management can be adapted in various dimensions (herd sizes, feed management, fertilizer management, adjusting cropping intensity and thus yields). This will generally result in lower compliance costs compared to studies which only consider fixed adaption options (e.g. Karl & Noleppa 2017).

Furthermore, the assumptions in FarmDyn imply that farm management is conducted under the FO 2007 and 2017 on the efficient technical and economic frontier, including fertilizing management. However, empirical results reveal high differences in the fertilizing management between farms (Osterburg & Techen 2012, p. 195; LWK NRW 2018b, p. 44), which hints at a high potential to increase nutrient use efficiency. Hence, inefficient farmers may actually save costs if they are pushed towards a more efficient fertilizer management by the FO 2017, especially through the compulsory fertilizing planning. This impact is not considered by our modelling approach.

We equally assume that farmers fully comply with the regulations of the FO 2007 and 2017 even if empirical results hint at past violations (LWK NRW 2014, pp. 54ff.). The FO 2017 also comprises measures which strengthen the enforcement, for instance higher penalties and improved data access for the enforcing governmental bodies. This could imply that some farms face costs and realize emission reductions by now complying with measures already in place under the FO 2007. Due to the lack of data, we cannot include this effect.

We identify manure export as the main compliance strategy of intensive pig farm types to comply with the stricter nutrient application thresholds. Manure export costs per unit are likely to rise due to the FO 2017 as more manure needs to be exported from livestock intensive regions, leading to longer transport distances. However, in supply-side models such as FarmDyn, per unit costs of manure transport are exogenous. As we have no data which allows us to update these costs under the FO 2017, we tend to underestimate related costs. Sensitivity analysis gives insights into the impact of price or cost changes on compliance costs (see Section 5.4.2 for sensitivity analysis on prices and compliance costs with the FO 2017), but cannot simulate price changes induced by the regulation. Here, manure allocation models estimate policy-induced manure flows and related costs (e.g. van der Straeten *et al.* 2012), but cover farming activities and compliance strategies to policies at a lower detail than farm models. Furthermore, transport is linked to environmental impacts outside the farm (Chapter 6), which are not covered by our assessment due to the chosen system boundaries.

The farm typology developed in Chapter 3 links the assessed farm types to the farm population by using the FSS. It allows the selection of the most dominant farm types and the evaluation of the importance of the most affected farms. However, the choice of which attributes define importance, for example area cropped or animal stock, remains subjective. Furthermore, missing or insufficient coverage of farm characteristics by the FSS introduces some uncertainty in the farm type definition. In our study, this is especially the case for the P soil status of farms and the manure storage capacity.

Furthermore, the FSS considers an individual legal unit as one farm and therefore, disregards the case that a farm may consist of multiple legal units. The latter is frequently observed for livestock farms in Germany which are divided, for instance for tax optimization, into several legal entities (Forstner & Zavyalova 2017, p. 12f.). Indeed, the most present pig fattening farm type in NRW, which covers 26.15% of the pig stock, does not hold any land (Appendix 3.B). It does not make sense to assess the impact of the FO on this type of legal unit without land, as almost all measures of the FO relate to the interaction of crop and fertilizer management. Equally, we are not able to link results for the analyzed farms to landless farm units without the necessary information on connections between them. Hence, a large share of the pig stock is most likely not represented by the pig farm types we assess.

4.4.3 SIMPLACE: Uncertainties in simulations of N dynamics

The dynamic simulation of the N balance in crop rotations at the regional scale comes with some challenges. The modelling approach in SIMPLACE requires information about the distribution of climate conditions and soil properties in space and time. The largest uncertainty regarding soil information in our study is related to soil properties, although the resolution of the soil map of NRW is the highest among the federal states in Germany (Grosz *et al.* 2017). Nevertheless, it is not possible to get access to soil layer specific information about the plant available P, pH and above all, the concentration of organic N in arable soils. The latter is strongly correlated with the soil organic matter content which is crucial for the simulation of the dynamics and quantities of N mobilization and immobilization. Currently this shortcoming, which is a general problem for model-based regional scale assessment of N dynamics in croplands, is overcome by starting model simulations with a spin-up or warm-up period of 10 to 20 years, before the targeted time period (Carvalhais *et al.* 2008; Foereid *et al.* 2012). In dynamic, process-based soil organic models with constant average climate and management conditions, this causes the initial soil organic matter content to shift towards a steady state condition and soil organic N content to be constant. This approach has been applied in our study, resulting in close to constant levels of soil organic N which depends on soil properties, climatic conditions, and management scenarios. Thus, the mineralization and immobilization of NO_3^- and ammonium at a certain location is not influenced by the initial amount of soil organic matter, which is highly uncertain, but rather by the respective site and management conditions. With this approach, the average N uptake in the storage organs of major crops is well simulated for the three SCR where the farm types analyzed in this study are located (Appendix 4.F, Appendix 4.G). However, this approach implies that the N removal by crops and NO_3^- leaching rates by the model are representing average values over a period of several years under steady state conditions, and do not represent the immediate impacts after a change in fertilizer management from FO 2007 to FO 2017.

4.4.4 Model connection

The coupling of crop and farm models is a powerful tool if the research objective requires precisely capturing cropping activities and related externalities. In the study at hand, it allows the representation of the yield impact of management options which change due to the revised FO. Furthermore, NO_3^- leaching, as the most prominent externality addressed by the FO, is precisely quantified thanks to the simulation with the crop system model.

The representation of other parts of the farming system by bio-physical models could further improve the validation of results. With regard to the impacts of the revised FO, N losses during storage and fertilizer application could be provided by bio-physical models with high detail and include variation due to weather and management. This would quantify the emission changes induced by policies, such as the FO, more precisely and show annual variations. However, the inclusion of data from bio-physical models into farm models comes at the price of increased model complexity and computing time. In our modelling set up, it is impossible to model farm populations or large-scale sensitivity analysis, as done in Chapter 5, and thus requires restricting the analysis to specifically selected farm types.

4.4.5 Policy implications

We identify farm types which face no or little adaptation needs to fulfill the requirements of the FO 2017. Besides arable farm types, this includes the extensive pig fattening farm type, which represents 9% of the pig stock in NRW. This means that a relevant share of farms faces no or low compliance costs due to the FO 2017 and therefore, will only slightly reduce environmental impacts, if at all. If frequent farm types covering larger shares of the area and livestock are not affected by the FO 2017, targeted improvements in environmental status will rest with the farms actually forced to reduce emissions. This mostly holds for intensive pig fattening farms that lose a considerable share of their standard gross margin and have an incentive for non-compliance. Hence, they should also be the target of enforcement activities but also of accompanying and support measures.

These findings lead to the question whether the FO 2017 is sufficient to fulfill related environmental targets, especially the requirements of the Nitrates Directive. Our results indicate that only a share of farms will realize emission reductions. To better address this question, future research should assess more farm types and link modelling approaches to environmental targets by upscaling to the regional scale. Overall, assessing the environmental impacts of the FO 2017 remains to some degree uncertain due to various data gaps, which include the level of non-compliance under the FO 2007. As explained above, we always assume full compliance that may lead to an underestimation of the environmental benefit of the FO 2017. Policymakers could make better-informed choices if legislation would increase data availability, along with enforcing measures. The FO 2017 already facilitates the collection of farm nutrient balances and fertilizer plans at the federal state level.

Our results indicate that the P_2O_5 surplus restrictions on highly P-enriched soils are the most binding measures for pig manure application and, hence, should be the focus of the enforcement. With this in mind, the current provision in the FO 2017 which allows farmers to take their own soil samples is clearly questionable. Furthermore, our results indicate that 6 months of manure storage are barely enough to bridge the legal manure banning periods. As manure application directly after the banning period in the spring is not always possible due to wet conditions, there is an additional incentive to apply manure in autumn beyond the legal limit. Over-application is far more difficult to control compared to the banning periods themselves. Policymakers should therefore consider making larger storage capacities mandatory for more farms. This is already a requirement in other EU countries such as Belgium and Denmark (Osterburg & Techen 2012, pp. 241ff.).

Manure transport from livestock intensive to arable farming dominated regions is promoted by policymakers (LWK Nds. 2018b) in order to lower the environmental burden of regional livestock concentration. Our results show clear economic gains for importing farms that should incentivize manure import. However, these results represent long-term benefits (Section 4.4.3) depending on the MFE given by SIMPLACE and rely on the assumption that manure importing farmers optimally replace chemical fertilizer. Furthermore, some obstacles to manure import are not covered by our analysis. Odor from manure application, unknown nutrient content and difficulties in planning are identified as barriers in a case study for organic fertilizers in Denmark (Case *et al.* 2017, p. 92). They hinder arable farmers in taking full advantage of the nutrients contained in manure, lowering its economic benefits and consequently reducing the willingness to accept manure. To fully utilize the potential of manure imports, policymakers could facilitate the building of manure storage in regions with arable farms and prescribe farmers to test the transported manure.

However due to manure imports, NH_3 volatilization and NO_3^- leaching increase on importing farms, as shown for the farm types ARAB-SB and ARAB-WR. This regional pollution swapping is of special concern if arable farms are close to sensitive areas, such as natural and semi-natural habitats, or in areas already exceeding environmental thresholds in water bodies. Policymakers should react to this by restricting and discouraging manure import to such areas. In Germany, for example, this can be done through the possibility of implementing additional measures under the FO 2017 in areas exceeding NO_3^- groundwater concentrations or P concentration in surface water.

In the calculation of nutrient application thresholds such as the fertilizer quota, standard factors for N losses for manure N are provided by the FO. In our analysis, the simulated N losses are mostly lower than the standard factors which allow higher N application as indicated by the threshold. In the fertilizing planning, for instance, only around 50% of excreted pig manure is accounted as plant available (Klages *et al.* 2017, p. 56), which makes the threshold non-binding for the pig farm types in our analysis. In future revisions of the FO, the standard loss factors should be reviewed and, if necessary, adapted to the present manure storage systems and application techniques. This stimulates efficient manure management by farmers as the N supply and yields may decrease if the MFE reflected by the standard loss factors are not realized.

4.5 Conclusion

We conclude from our analysis that the impact of the FO 2017 on the economic and environmental performance of farms highly depends on farm characteristics. The revised FO results in high emission reductions for the intensive pig fattening farm type which is linked to the high compliance cost of 2.32 € pig^{-1}. In the contrary, the farm type representing extensive pig fattening faces costs of only 0.42 € pig^{-1}, mostly reflecting the required adaptation of low-emission manure application techniques. It causes relevant reductions of NH_3 volatilization, but NO_3^- leaching almost remains unchanged. On arable farm types, manure import triggered by the FO causes a relevant cost decrease by 98 and 108 € ha^{-1}, but leads to an increase in NO_3^- leaching and NH_3 volatilization. Methodologically, the model connection proved a helpful tool for jointly and consistently analyzing economic and environmental impacts of agri-environmental policies. Due to its generic nature, it can be used to assess upcoming revisions of the FO and the implementation of the Nitrates Directive in other German regions or EU member states. The quantification of N response of crops and NO_3^- leaching would benefit from an improved data base, especially relating to soil organic matter content in arable soils for crop modelling. Future research should link the farm to the regional scale and thereby relate emission reduction to the existing environmental targets.

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Chapter 5

On-farm compliance costs with the EU Nitrates Directive: a modelling approach for specialized livestock production in Northwest Germany[4]

Abstract

In the EU, several environmental regulations aim at protecting the environment from agricultural nitrogen and phosphorus losses. The German regulation on farmers' nutrient management, especially implementing the EU Nitrates Directive, was revised in 2017. It comprises considerable tightening of numerous measures and costs for farmers to comply with. We provide the first systematic farm-level analysis of compliance costs of the recent revision in a case study for the federal state of North Rhine-Westphalia. To do so, we apply a bio-economic optimization model at farm-level to a representative sample of specialized dairy and pig farms. The sample is derived by Latin Hypercube sampling based on the observed distribution of farm characteristics from official agricultural statistics. Modelling results are evaluated by grouping of farms and a statistical meta-model. Results show highly heterogeneous compliance costs reaching from 0 to 2.66 Euro (€) per pig and 0 to 0.83 cent (ct) per kg milk. 47.3% of pig and 38.4% of dairy farms do not face any costs. Pig farms with high compliance costs are characterized by high stocking density, the absence of low-emission manure application techniques and phosphorus-enriched soils. Dairy farms with high compliance costs have no low-emission manure application techniques and a high share of grassland. For dairy farms, stricter thresholds for nutrient application do not cause any compliance costs. The meta-model reveals the large effect of prices and assumptions regarding the fertilizer management on compliance costs. Results are of relevance beyond the case study area as other regions in the EU have a similar agricultural structure and need to fulfil the same EU directives. Policymakers need to be aware that high compliance costs increase the incentive of non-compliance and also consider heterogeneous impacts when

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designing complementary policies. Future research should focus on long-term adaption of farmers and include transaction costs as well as technical progress.

5.1 Introduction

The loss of reactive nitrogen (N) and phosphorus (P) from farming systems pose a threat to biodiversity, climate, and human health (Sutton *et al.* 2013, pp. 32ff.). In the EU, several regulations aim at limiting the N, mainly nitrate (NO_3^-), ammonia (NH_3), and nitrous oxide (N_2O), and P emissions from agriculture. The Nitrates Directive (European Council 1991) is the core regulation to limit nutrient loss from farming systems and primarily aims at the protection of ground and surface waters from NO_3^-. Further regulations target NH_3 emissions in the air and P entry into surface waters.

Costs of reducing these emissions on farm are either reported as abatement or compliance costs. (Marginal) abatement costs of a farm are directly related to an (additional) emission reduction (McKitrick 1999, p. 306) or to the reduction of a corresponding indicator (Lengers *et al.* 2014, p. 580). Their calculation assumes that the firm selects the cost-minimal abatement strategy. In contrast to that, compliance costs refer to changes imposed by a legal regulation (Uthes *et al.* 2010, p. 287; Mack & Huber 2017, p. 35f.) which prescribes specific abatement practices. Hence, compliance costs do not necessarily give insights into cost-effectiveness or cost-efficiency of policies but rather assess firms' costs. Multi-target policies, such as most regulations on nutrients from agriculture, relate to numerous emissions. That renders the calculation of abatement costs challenging or even misguiding. In contrast, compliance costs give insights into economic consequences of legal changes without requiring emission accounting.

In Germany, the legal measures to lower the loss of N and P from farming systems are primarily laid out in the Fertilization Ordinance (FO) which was last revised in June 2017 (BMEL 2017a). The revision process was triggered by infringement proceedings, which were initiated by the European Commission after Germany had missed water quality benchmarks (BMU & BMELV 2012, pp. 7ff.). Hence, the FO is the German "action programme" to implement the Nitrates Directive. It also comprises measures to lower P and NH_3 losses and is therefore linked to the environmental targets laid down in the EU Water Framework Directive (WFD) (European Parliament, European Council 2000) and the EU Directive on the Reduction of National Emissions of Certain Atmospheric Pollutants (European Parliament; European Council 2016). The revised FO introduces considerably tighter measures, such as stricter thresholds for the application of chemical fertilizer and manure and the fading out of certain manure application techniques (Chapter 2). A detailed analysis on the associated compliance costs for farmers is still missing.

Menghi *et al.* (2015, pp. 74ff., 139ff.) compare the costs for typical farms to comply with the Nitrates Directive and other environmental regulations across Europe based on expert knowledge and an engineering approach. They estimate the costs induced by the Nitrates

Directive in 2010 as 0.04% to 0.57% of total farm costs for dairy and pig farms in Germany and identify the legally required manure storage as a major cost factor. Belhouchette *et al.* (2011) combine a bio-economic farm model and a crop growth model and observe considerable changes of cropping patterns to fulfil the Nitrates Directive commitments, but no relevant impact on farm income for arable farms in Southern France. Manure allocation models, as applied by van der Straeten *et al.* (2012) to a region in Belgium, take spatial interaction between farms into account and determine aggregated manure transport costs. In doing so, they provide insights into a central driver of compliance costs. Micro data at farm-level can be used, as Buckley *et al.* (2015) show, to estimate the nutrient use efficiency of farms. Such analysis can give insights on the potential cost saving due to increased nutrient use efficiency as a compliance strategy to fulfill stricter regulations on nutrient application. Generally, scientific literature finds highly heterogeneous compliance and abatement costs amongst farms, with regard to regulations targeting the reduction of nutrient losses (Menghi *et al.* 2015, pp. 126ff.; Wagner *et al.* 2017, pp. 74f.) as well as other environmental externalities (Mack & Huber 2017, pp. 38f.; Uthes *et al.* 2010, pp. 288f.; Huber & Flury 2017, pp. 15f.).

Given that studies on agri-environmental regulations find large differences in compliance costs across farms, a proper assessment should report the distribution of costs in the farm population, in order to better assess economic trade-offs that are faced when improving environmental quality. This requires datasets on the population with enough detail to distinguish impacts between farms. In order to do so, some studies mainly rely on the Farm Accountancy Data Network (FADN) (Uthes *et al.* 2010, p 285; Mack & Huber 2017, p. 35) as a more general purpose stratified random sample. We instead use data from the German Farm Structure Survey (FSS). Compared to the FADN, the German FSS includes fewer farm characteristics, especially regarding economic variables. However, the FSS covers almost all farms instead of only a sample and includes precise information on farm location, manure application techniques and manure storage capacities, which are needed for the study at hand. Strict German privacy protection regulations do not allow the extraction of single farm data from these sources. Therefore, we apply a sampling approach which creates a representative farm sample based on the observed distribution of relevant farm characteristics.

The contribution of this research is hence threefold. First, we provide a methodology to create a representative farm population under restricted data accessibility for environmental assessments where samples such as FADN might not comprise the needed farm characteristics. Second, we show how compliance costs for such a farm population can be extracted, summarized and analysed. And third, we contribute a detailed analysis of the distribution and drivers of on-farm compliance costs under the 2017 revision of the FO implementing the Nitrates Directive in Germany. Comparable measures can also be found in regulations across Europe and internationally such that our results are of interest beyond Germany. Knowledge of the compliance costs is of importance for the target-oriented design of complementary measures, for instance financial support programs for technology adaptation, and for future implementation of agri-environmental regulations.

5.2 The 2017 revision of the German Fertilization Ordinance

The FO encompasses numerous and partly interlinked measures to lower NO_3^-, NH_3, and P losses. For our analysis, we select the most relevant measures with regard to compliance costs (Table 5.1; see Chapter 2 for a complete summary of FO 2017).

Three different thresholds limit the nutrient application to crops. First, under the FO 2017 farmers are obliged to apply a clearly defined so-called “fertilizing planning” approach which calculates the N need of crops and from there, derives their maximal fertilizer doses. This limits the application of chemical fertilizer and manure which is accounted with predefined mineral fertilizer equivalents (MFE). Second, the application of manure N is limited to 170 kg N ha^{-1} on farm average which creates an interlinkage between animal stock and managed land. This threshold is equal under the FO 2007 and 2017, but the latter introduces lower loss factors for pig manure which correspond to a reduction of the target value. Third, farmers have to calculate N and phosphate (P_2O_5) soil surface balances under the FO 2007 and 2017, juxtaposing nutrient input via manure and chemical fertilizer with removal via the harvested crop. The nutrient surplus is not allowed to exceed a target value in a sliding multi-year average. Moving from FO 2007 to 2017, the permitted surplus is lowered from 60 to 50 kg N ha^{-1} for N and from 20 to 10 kg P_2O_5 ha^{-1} for P. No P_2O_5 surplus is allowed on P-enriched soils (according to the FO, >0.0002% P_2O_5 in soil applying the calcium-acetate-lactate method). These measures in combination ensure a certain nutrient use efficiency and limit the amount of chemical fertilizer and manure which can be applied. Which among these will be the most binding threshold for manure application on livestock farms depends on the $N:P_2O_5$ ratio of excreted manure and of plant nutrient need.

Table 5.1 Key measures of the Fertilization Ordinance 2007 and 2017

Measure	Fertilization Ordinance 2007	Fertilization Ordinance 2017
Fertilizing planning	Unspecified and non-binding fertilizing planning	Clearly defined and compulsory fertilizing planning
Organic N application – threshold	170 kg N $ha^{-1}a^{-1}$ N from animal sources	170 kg N $ha^{-1}a^{-1}$ N from animal and plant sources (biogas digestate from plant origin); lowering of accountable loss factors
Nutrient surplus thresholds	60 kg N $ha^{-1}a^{-1}$ 20 kg P_2O_5 $ha^{-1}a^{-1}$	50 kg N $ha^{-1}a^{-1}$ 10 kg P_2O_5 $ha^{-1}a^{-1}$; 0 kg P_2O_5 $ha^{-1}a^{-1}$ on P-enriched soils[b]
Banning periods – fixed	Grassland 15.11-31.1 Arable land 1.11-31.1	Grassland 1.11-31.1 Arable land 1.10-31.1
Banning periods – after harvest of the main crop	Organic nutrient application restricted to 40 kg ammonia N or 80 kg total N for catch crops, winter crops, and straw rotting	Total nutrient application restricted to 30 kg ammonia N and 60 kg total N for catch crops, winter rapeseed, field forage and winter barley following cereals in crop rotation
Manure application techniques	Broadcast spreader allowed	Broadcast spreader banned except on bare land followed by prompt incorporation; compulsory from 2020 onwards on arable, 2025 on grassland
Minimum manure storage capacity	6 months[a]	6 months, 9 months for farms >3 livestock units ha^{-1}

Source: own illustration based on BMELV 2007 and BMEL 2017a; [a] defined in Federal law on requirements for manure storage facilities; [b] according to the Fertilization Ordinance, >0.0002% P_2O_5 in soil applying the calcium-acetate-lactate method; N - nitrogen; P_2O_5 - phosphate; P - phosphorus

The application of manure, especially in autumn and winter, carries the risk of NO_3^- leaching (Cameron *et al.* 2013, p. 151; Di & Cameron 2002, p. 246). Therefore, the FO does not allow manure application during certain months, restricts the application in autumn and prescribes minimum storage capacities for manure. Under the FO 2017, the banning periods are extended and a reduced number of crops are allowed to receive fertilizer in autumn. Furthermore, farms which exceed 3 livestock units (LU) ha^{-1} have to provide a minimum manure storage capacity of 9 instead of 6 months.

As the chosen manure application technique highly impacts NH_3 volatilization (Webb *et al.* 2010, pp. 44ff.), the FO defines the allowed techniques. The FO 2017 now prescribes the use of low-emission manure application techniques on cropped land and grass land. Thus, broadcast spreading is no longer allowed after a transition period except for manure application on bare land followed by prompt incorporation.

To adapt to the described measures, farms can select different compliance strategies which result in specific costs (Section 5.3.2). In summary, the changes in the FO 2017 generally lead to costs for the following farms.

(1) Farms exceeding the stricter nutrient application thresholds

(2) Farms exceeding 3 LU ha^{-1} and having manure storage capacities below 9 months

(3) Farms not yet using low-emission manure application techniques

5.3 Material and methods

We develop a three-step modelling framework to assess on-farm costs to comply with the revised FO for dairy and pig production (Figure 5.1). More specifically, we adopt and extend a meta-modelling approach originally developed by Lengers *et al.* (2014, pp. 582ff.) to assess marginal abatement costs of greenhouse gas emissions from dairy farms.

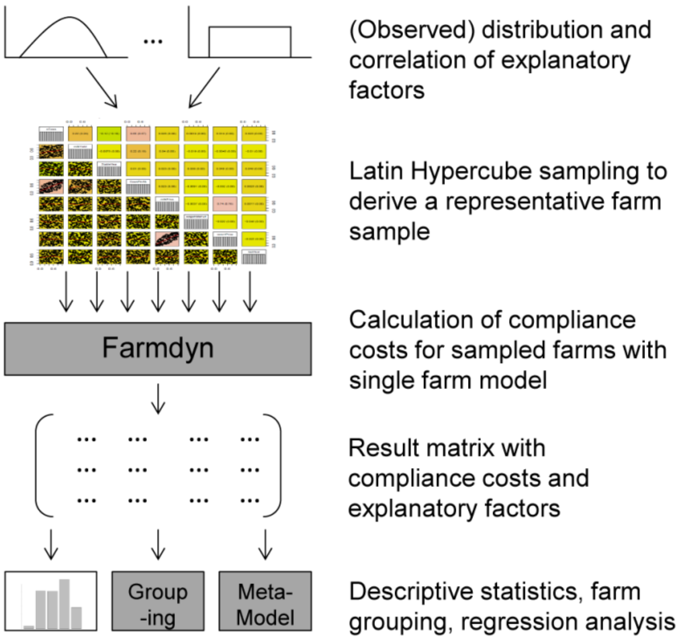

Figure 5.1 Overview of modelling framework

Source: own illustration based on Lengers et al. (2014, p. 583)

As the first step, a representative farm sample is generated by Latin Hypercube sampling (LHS). The sampling is based on descriptive statistics of the farm population derived from official statistics and additional sources (Section 5.3.1). Second, profits for each farm in the generated farm sample are simulated in the single farm optimization model FarmDyn for both the FO 2007 and 2017. The profit differences quantify the on-farm compliance costs of the revised FO 2017. Thereby, the model captures in detail the measures of the respective regulation as well as the most prominent compliance strategies (Section 5.3.2). Third, these results are used in a descriptive statistical analysis to assess the distribution and drivers of compliance costs (Section 5.3.3). Furthermore, the sampling procedure is repeated with additional explanatory variables which are not covered by official agricultural statistics. Based on the results, a statistical meta-model is derived to detect and quantify further drivers of compliance costs. It provides insights into the impact of key assumptions on parameters which are not covered in statistics (Section 5.3.4).

5.3.1 Explanatory variables and sampling procedure

Our analysis focuses on farms specialized in pig fattening and dairy production in the federal state of North Rhine-Westphalia (NRW). NRW is the fourth largest of the 16 German states by total land area with 33,600 farms in total (Section 3.3). It hosts 27% of the German pig and 10 % of the German dairy stock (Destatis 2017, p. 7, 19). There are 4,322 specialized dairy and 3,165 pig fattening farms, which comprise 12.8% and 9.4% of all farms and account for 83.4% of all dairy cows and for 56.4% of all fattening pigs in NRW (Appendix 3.B). Specialized livestock farms are mostly concentrated in the Northwest planes of NRW. These regions are characterized by high regional organic nutrient emergence. In contrast, low mountain ranges comprise less intensive dairy farming with lower regional nutrient emergence (Appendix 3.D; LWK NRW 2018, pp. 58ff.).

Due to data privacy laws, we cannot simulate observed farms as access to single farm records from the German FSS is not available. Instead, we construct a representative farm sample based on the distribution of farm characteristics. The selected farm characteristics reflect drivers linked to required adaption to the FO 2017 and related costs (Section 5.2). The stocking density determines the amount of legally accounted nutrients excreted in relation to available land and is directly or indirectly linked to all changed measures in the FO 2017. It determines to a large extent the need to adapt to stricter nutrient application thresholds. Furthermore, the requirement to increase the manure storage capacity from 6 to 9 months is depending on the stocking density. This measure also motivates to include the existing storage capacity as a farm characteristic. Similarly, the currently used manure application techniques are included as a farm characteristic due to now compulsory low-emission manure application techniques in the FO 2017. The share of grassland as a further characteristic is likely to influence compliance costs of dairy farms for two reasons. First, the required low-emission application techniques under the FO 2017 are more costly on grassland than on arable land (KTBL 2018a). Second, legally allowed nutrient surpluses in the FO depend on the accounted nutrient removal of crops which is especially high on intensive grassland. The allowed P_2O_5 surplus depends on the P soil status which is therefore included as a characteristic as well. Finally, we included the farm size in ha as a characteristic. It determines in combination with the stocking density the total herd size which is linked to economies of scale, for instance regarding investment in storage capacities as storage costs per m^3 decrease with storage size (KTBL 2016, p. 153).

Whenever available, we rely on single farm data from the FSS 2016 (Table 5.2). The manure storage capacity is taken from the FSS 2007, summarized by Osterburg & Techen (2012, p.

176), as it is not covered by the 2016 survey. Furthermore, the soil P-status is included by regional data from Jacobs (2014) and linked via the farm location to the assessed farms. P-enriched soils as well as low-emission manure application techniques are introduced as binary variables, being either present at a farm or not (see Appendix 5.B for detailed description of assumptions).

LHS, described by McKay *et al.* (1979), is used to generate a sample of 10,000 dairy and pig farms, respectively, a sample size which provides a sufficient coverage of the distribution of farm characteristics in the entire population by the meta-model. LHS splits the cumulative distribution functions of the described farm characteristics into equal intervals. One sample is selected from each interval of a variable and combined with the selected interval of the other variables. This ensures that the whole range of a variable is represented in the sample. The LHS is carried out using the R package 'lhs 0.10'.

Table 5.2 Characterization and sources of explanatory variables

Explanatory factors	Farm type	Minimum	Median	Maximum	Data source
Farm size [ha]	Dairy	8.14	61.24	221.35	FSS 2016[2]
	Pig	6.84	48.20	159.05	
Grassland share [%]	Dairy	0.06	0.51	1	FSS 2016[2]
	Pig	-	-	-	
Stocking density [LU ha^{-1}]	Dairy	0.63	1.75	5.94	FSS 2016[2]
	Pig	1.11	2.06	14.82	
Manure storage capacity [m]	Dairy	6.00	8.00	8.00	FSS 2007 in Osterburg & Techen (2012)
	Pig	6.00	8.00	8.00	
Low-emission application techniques [1/0][1]	Dairy	0	0	1	FSS 2016[2]
	Pig	0	0	1	
P-enriched soils [1/0][1]	Dairy	0	1	1	Jacobs (2014), FSS 2016[2]
	Pig	0	1	1	

[1] low-emission application techniques and P-enriched soils are introduced as binary variables; [2] detailed source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation. See Appendix 5.E and Appendix 5.F for whole data set; FSS - Farm Structure Survey; LU - livestock unit; P - phosphorus

Regular LHS assumes that there is no correlation between the sampled variables and, hence, the combination of intervals is random. To represent the farm population covered by the FSS 2016, we introduce an algorithm from Iman & Conover (1982) which ensures that pairing of the intervals converges with the observed correlations. Correlations between key explanatory variables are calculated based on the FSS 2016 and the Agricultural Census 2010 (Appendix 5.C, Appendix 5.D). The correlation factor between soil P status and stocking density is set to 0.3, based on regional data which hints at this interlinkage (Osterburg & Techen 2012, p. 201).

5.3.2 Farm-level modelling

Profit maximizing farm programs are simulated with FarmDyn; a generic, bio-economic, single farm optimization model based on mixed-integer linear programming (Lengers *et al.* 2013; Lengers *et al.* 2014; Schäfer *et al.* 2017). It assumes a fully informed and completely rational decision maker. FarmDyn contains detailed information on bio-physical and economic processes derived from planning data, official statistics, and expert knowledge. It is parameterized for Germany, covering pig fattening and dairy production in NRW. The following paragraph points out important elements of FarmDyn with regard to the study at hand; a complete and up-to-date model documentation is available online (Britz *et al.* 2018). In addition, Appendix 5.H comprises important input-output coefficients.

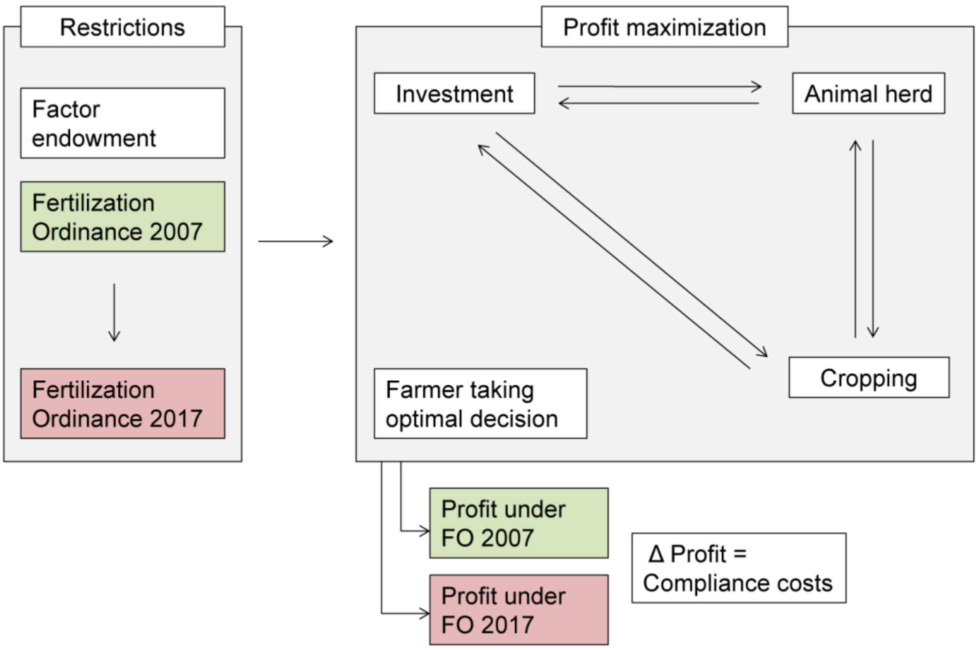

Figure 5.2 Estimation of on-farm compliance costs with the Fertilization Ordinance 2017 in FarmDyn

Source: own illustration; FO - Fertilization Ordinance

On-farm compliance costs with the FO 2017 are derived in a comparative-static setting. First, FarmDyn maximizes annual profits under the restrictions of the FO 2007 (Figure 5.2). The profits are defined as the revenue from selling products minus costs for intermediate inputs and new investments, while labour and land are assumed to be farm owned. The model is calibrated to the observed animal stock, assuming that investments into stables and technology are sunk costs. In a second iteration, the restrictions from the FO 2007 are replaced by the stricter ones from the FO 2017. This allows quantifying the on-farm compliance costs as the change in profit moving from FO 2007 to 2017. For the comparison to the gross margins and cost items of pig and dairy farms, compliance costs are calculated per pig and per kg energy-corrected milk (ECM), respectively. ECM is standardized milk which contains 4% fat and 3.4% protein (KTBL 2014, p. 821). As the FO 2017 may induce a change in animal stock, the compliance costs are related to the number of animals under the FO 2007 and, thereby, capture also costs of a reduced stocking density under the FO 2017.

Table 5.3 Overview on measures of the Fertilization Ordinance and corresponding compliance strategies in FarmDyn

	Fertilizing planning	Organic N application threshold	N surplus threshold	P_2O_5 surplus threshold	Banning periods	Manure application techniques requirements	Manure storage capacity requirements
Reduced stocking density	X	X	X	X	X	X	X
Manure export	X	X	X	X	X	X	
Changed feeding	X	X	X	X			
Increased nutrient removal (e.g. straw)	X		X	X			
Catch crops					X		
Investment into manure storage					X		X
Investment into low-emission application techniques						X	

Source: own illustration; N - nitrogene; P_2O_5 - phosphate

FarmDyn provides different strategies which can be used to comply with measures of the FO. First, farms may have to adapt to stricter nutrient application thresholds (Section 5.2). To do so, farmers can increase nutrient removal via manure and straw export. Furthermore, FarmDyn depicts different pig feeding strategies differentiated into feeding phases and related nutrient needs which is reflected in corresponding N and P_2O_5 excretion rates. In line with the FO, we differentiate between standard, reduced N-P and strongly reduced N-P feeding regimes. Second, the FO 2017 requires farmers to increase their manure storage capacity when exceeding 3 LU ha^{-1}. Here, FarmDyn covers investment and operating costs for additional manure storage. The reduction of the animal stock and thus of the livestock density is a further strategy to avoid an investment into manure storage as well as to comply with nutrient application thresholds. Third, FarmDyn includes relevant manure application techniques and corresponding costs to assess that farms have to adapt low-emission manure application techniques. We assume application by trailing hose on arable land and by trailing shoe on grassland. The adaption of new technology is linked to high investment costs for single farms and, therefore, FarmDyn does not take these technologies into account as investments but as services offered by a contractor and paid for by the farmer as it is a characteristic practice in NRW.

The impact of the nutrient application thresholds highly depends on the assumptions regarding the fertilizer management. We assume that farmers follow the prescribed fertilizing planning from the FO 2017. The FO 2007 only recommended fertilizing planning such that farmers could apply manure until the allowed N and P_2O_5 surplus or the organic N application threshold are reached. We however use the fertilizing approach both under the FO 2007 and 2017 to define the fertilizer use of farms.

Furthermore, the substitutability of manure and chemical fertilizer needs to be defined. The FO 2017 prescribes MFE for the fertilizing planning which are used in FarmDyn. However, only a limited share of total crop nutrient need can be provided as manure due to agronomic restrictions. This is reflected in FarmDyn by introducing minimum chemical fertilizer needs of crops based on expert judgement, being 20 kg P_2O_5 ha^{-1} and 8 kg N ha^{-1} for maize used for silage or corn-cob-mix and 40 kg N ha^{-1} for winter wheat and winter barley. Grassland can be sustained completely on nutrients from manure (Gaiser 2018a). Typical crop rotations for pig and dairy farms are based on the crop shares derived from the FSS 2016 and expert judgement (Gaiser 2018b). The crop rotation is winter wheat, winter barley and maize for corn-cob-mix on the pig farms and winter wheat, winter barley and maize for silage on dairy farms.

5.3.3 Grouping of farms

Grouping of farms according to the compliance costs gives valuable insights into their drivers as results from Mack & Huber (2017, pp. 38f.) show. We apply that approach in our study to the results for 10,000 farms generated by the single farm modelling. Group boundaries are chosen by the help of descriptive statistics and aim at summarizing farms with similar cost drivers. For continuous variables, the Kruskal–Wallis test is used to detect significant difference between means of groups. For post-hoc testing, we apply the Dunn's Test of Multiple Comparisons, using the R package ‘dunn.test’ 1.3.5. The Bonferroni correction prevents the multiple comparisons problem. For categorical variables, significant difference between groups is estimated by creating contingency tables and applying the Fisher's exact test of independence. We carry out the Post-hoc testing for categorical variables with the help of the R package ‘rcompanion’ 2.0.0. Here, too, the Bonferroni correction is used to prevent the multiple comparisons problem.

5.3.4 Statistical meta-model

For the statistical meta-model, the sampling approach is repeated (Section 5.3.1). We consider additional explanatory variables for which economic insight suggests an impact on compliance costs and which are not covered by the FSS or other data sources mentioned above. Specifically, we add the output prices (pork meat or milk), the straw price, the export manure costs, the costs for manure application dependent on technology, the minimum chemical fertilizer need of crops, and the MFE. The detailed methodology and factor ranges are described in Appendix 5.A. We repeat the sampling procedure and the farm modelling for samples of 10,000 pig and dairy farms, respectively. The result matrices are used to run multiple linear regression models, separately for dairy and pig production.

5.4 Results

The simulated on-farm compliance cost with the revised FO for dairy and pig farms in NRW are highly heterogeneous, based on the distribution of the observed farm characteristics (Table 5.2). They range from 0 to 2.66 € pig^{-1} (Figure 5.3) and from 0 to 0.83 ct (kg ECM)$^{-1}$ (Figure 5.4). Average compliance costs are 959.99 € per farm or 0.29 € pig^{-1} for pig farms and 1,715.63 € per farm or 0.21 ct (kg ECM)$^{-1}$ for dairy farms. However, a high share of farms, 47.3% of pig farms and 38.4% of dairy farms, do not face any compliance costs.

5.4.1 Drivers of compliance costs

In order to identify drivers of compliance costs, we group the dairy and pig farms by their compliance costs and analyze group differences in main farm characteristics (Table 5.5). Furthermore, the statistical meta-model which includes farm characteristics as explanatory variables gives insights into their average impact on compliance costs (Table 5.4).

Pig farms

Pig farms having low-emission manure application techniques in place and a stocking density between 1.11 and 2.89 LU ha^{-1} do not face any costs. These farms are found in the group without compliance costs (Table 5.5) which holds 47.3% of all pig farms. In this range of stocking density, farms do not have to adapt to stricter nutrient application thresholds or invest into additional manure storage capacities. However, 14.02 % of farms in the group without compliance costs do not yet apply low-emission application techniques. They are characterized by low stocking densities, ranging from 1.11 to 1.47 LU ha^{-1}. These farms can continue to broadcast spread all their manure, distributing it completely on bare land followed by prompt incorporation which is allowed under the FO 2017.

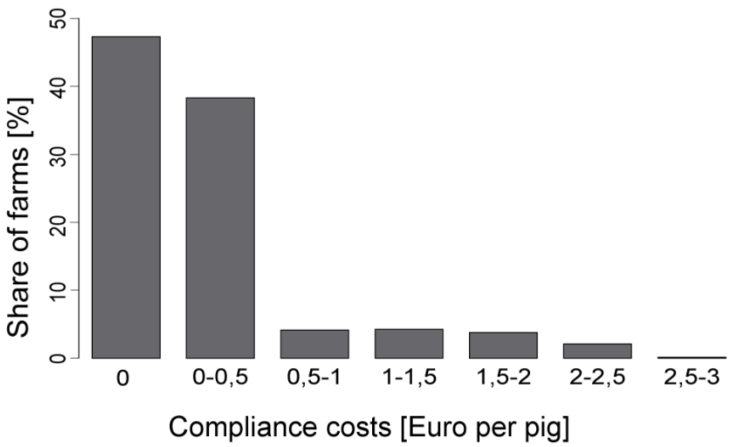

Figure 5.3 Distribution of on-farm compliance costs with the Fertilization Ordinance 2017 for specialized pig farms in the German federal state of North Rhine-Westphalia

Source: own calculation and illustration

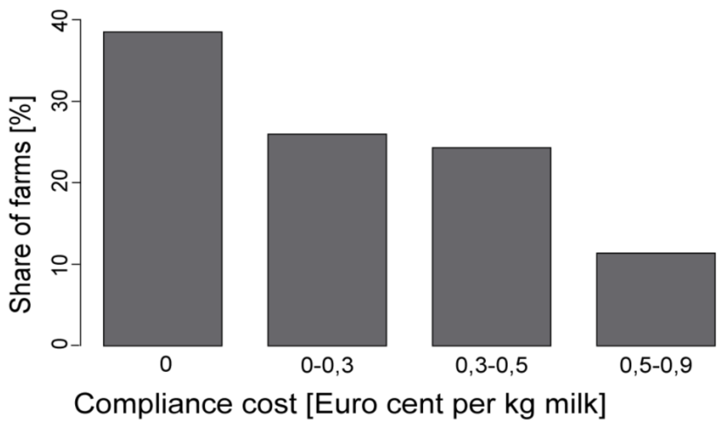

Figure 5.4 Distribution of on-farm compliance costs with the Fertilization Ordinance 2017 for specialized dairy farms in the German federal state of North Rhine-Westphalia

Source: own calculation and illustration

Generally, the lack of low-emission manure application techniques is a major cost driver. The statistical meta-model returns an average cost decrease of 0.19 € pig^{-1} when the technology is already available (Table 5.4). Farms without the technology but no further need for adaption are the vast majority of the group with compliance costs between 0 and 0.5 € pig^{-1}. This group is characterized by a relatively low stocking density (mean of 2.13 LU ha^{-1}) which makes adaption to the stricter nutrient application thresholds or the investment into additional manure storage capacity unnecessary.

Farms with stocking densities above 2.88 LU ha^{-1} face costs for such further adaptions and are found in the groups from 0.5 to 1.0 € pig^{-1} up to 2.5 to 3.0 € pig^{-1}. Farms in these groups represent a share of 14.42% of all farms.

These farms face additional compliance costs to adapt to stricter nutrient application thresholds, which is linked to the stocking density and the soil P status. The P surplus restriction is most binding for manure application, caused by the N:P_2O_5 relation between pig manure and crop need. Farms having P-enriched soils need to lower their P surplus to 0 instead of to 10 kg P_2O_5 ha^{-1}. Hence, having P-enriched soils increases compliance costs for farms which is reflected in the statistical meta-model with an average compliance costs increase of 0.05 € pig^{-1}.

Furthermore, the costs related to fulfill the stricter P surplus are linked to the stocking density of farms. The effect of stocking density is twofold. First, higher stocking density increases the need for adaption and the costs of farms to fulfill the stricter P surplus threshold as the P surplus is higher. Farms adapt by changing their feeding regimes and, as the most dominant compliance strategy, by exporting manure. This causes the significant different stocking densities between the groups with costs of 0 to 0.5 and 0.5 to 3.0 € pig^{-1}. Second, the stocking density has a reducing effect on the compliance costs per pig for farms having more than 3.8 LU ha^{-1}. Farms with a stocking density between 3.8 and 14.82 LU ha^{-1} face the same costs per ha to meet the P_2O_5 surplus threshold. Farms with a stocking density between 3.8 and 14.82 LU ha^{-1} are already limited by the P surplus threshold under the FO 2007 with resulting manure exports. Facing the same manure export costs and the same P surplus reduction requirements to reach a 10 or 0 kg P_2O_5 ha^{-1} leads to the same costs per ha. However, from 3.8 to 14.82 LU ha^{-1} the compliance costs per pig decreases as the same costs per ha are distributed over a larger number of pigs. On average, compliance costs increase by 0.11 € pig^{-1} for an additional LU ha^{-1} as derived from the meta-model.

Table 5.4 Statistical meta-models of the single farm model FarmDyn on on-farm compliance costs (dependent variable) with the Fertilization Ordinance 2017 for dairy and pig farms in the German federal state North Rhine-Westphalia

	Pig farms	Dairy farms
Intercept	0.1178	0.1832***
Farm size [ha]	-0.000039	-0.00018***
Grassland share [%]	-	0.2292***
Stocking density [LU ha^{-1}]	0.1109***	0.0438***
Manure storage capacity [m]	-0.0378***	-0.00636***
Low-emission manure application techniques [dummy]	-0.1903***	-0.3052***
P-enriched soils [dummy]	0.0507***	-0.0037
Pork price [€ (kg carcass weight)$^{-1}$]	0.3314***	-
Milk price [€ (kg ECM^{-1}]	-	-0.00036
Straw price [€ t^{-1}]	0.000068	0.000044
Manure export costs [€ m^{-3}]	0.0085***	0.000409*
Manure application costs [€ m^{-3}]	0.0642**	0.1771***
Minimum chemical fertilizer need [kg ha^{-1}a^{-1}]	0.0712***	0.0105***
Mineral fertilizer equivalents [%]	-0.5161***	0.000755
Multiple R-squared	0.2707	0.7562
Adjusted R-squared	0.2699	0.7559

*Source: own calculation and illustration; *, ** and *** indicates significance at 0.01, 0.001 and 0 level; € - Euro; ECM - energy-corrected milk; LU - livestock units; P - phosphorus*

The need to invest into new manure storage capacity is related to the stocking density as it is required for farms exceeding 3 LU ha^{-1}. Farms which face costs for additional manure storage capacity are found in the groups having compliance costs of 0.5 to 1 up to 2.5 to 3.0 € pig^{-1}. Having already higher manure storage capacity in place lowers compliance costs as shown by the average cost decrease of 0.04 € pig^{-1} for an additional month of manure storage. Farms with a stocking density slightly above 3 LU ha^{-1} avoid the investment into additional manure storage capacities by reducing their stocking density below 3 LU ha^{-1}.

Pig farms with the highest compliance costs, found in the groups from 2.0 to 2.5 and 2.5 to 3.0 € pig^{-1}, combine all cost driving farm characteristics and hold a share of 2.26% of total pig farms.

Dairy farms

The drivers of compliance costs for specialized dairy farms differ from pig farms. Dairy farms do not need to adapt to the changed nutrient application thresholds. This is caused by the different N:P_2O_5 relations in cattle manure such that the stricter threshold with regard to the P_2O_5 surplus becomes non-binding. Rather, the application threshold of 170 kg manure N ha^{-1} already found under the FO 2007 remains relevant for maximal manure application rates.

Thus, the main drivers of compliance cost are the obligatory use of low-emission manure application techniques and the necessary investment in additional manure storage capacity when exceeding 3 LU ha^{-1}.

There are 38% of dairy farms which do not face any compliance costs. Out of the 38%, 98% of farms already use low-emission manure application techniques. The remaining 2% can incorporate all their manure on bare land after broadcast spreading. They are characterized by a low stocking density (0.62 - 0.85 LU ha^{-1}) and a low share of grassland (11.64% - 36.07%). Furthermore, farms in this group have stocking densities below 3 LU ha^{-1} and, hence, do not have to invest into additional manure storage capacity.

The absence of low-emission manure application technique is the main cost driver for dairy farms. The meta-model returns an average cost decrease of 0.31 ct (kg ECM)$^{-1}$ when the technology is already used. The costs to adapt the new technology increase with an increasing share of grassland as can be seen in the significant different mean grassland share in the groups 0 to 0.3, 0.3 to 0.5, and 0.5 to 0.9 (kg ECM)$^{-1}$. The reasons are twofold. First, farms with a high share of arable land can partly avoid the use of the expensive technology by broadcast spreading manure to bare land followed by prompt incorporation. Second, the application with trailing shoe, used on grassland, is slightly more expensive than using a trailing hose on arable land. Therefore, the compliance costs increase by 0.002 ct (kg ECM)$^{-1}$ for 1% higher share of grassland.

In the groups of farms with costs above 0.3 € ct (kg ECM)$^{-1}$, there are also farms present which already have the low-emission application techniques in place. These farms are characterized by a stocking density above 3 LU ha^{-1} and the need to invest into additional manure storage vessels to provide manure storage capacities for 9 months. 11.5% of the total assessed dairy farms exceed a stocking density of 3 LU ha^{-1}. Already having a storage capacity for 8 instead of 6 months in place reduces average compliance costs by 0.013 ct (kg ECM)$^{-1}$ as shown by the meta-model. The costs for additional manure storage vary between the farms due to economies of scale as the investment in large manure storage vessels leads to lower costs per m^3 of manure stored.

Table 5.5 Grouping of specialized dairy and pig farms showing similar compliance costs with the Fertilization Ordinance 2017 in the German federal state of North Rhine-Westphalia

Pig farms

Compliance cost group [€ pig^{-1}]	0	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0
Stocking Density [LU ha^{-1}]	1.83[a] ±0.49	2.13[b] ±0.44	6.52[c] ±5.20	5.28[c] ±3.34	4.20[c] ±1.22	3.85[c] ±0.45	3.76[c] ±0.16
Land [ha]	61.04[a] ±33.50	48.42[b] ±31.18	45.58[b] ±28.14	47.56[b] ±32.85	47.06[b] ±31.07	46.75[b] ±26.61	17.27[c] ±12.37
Manure Storage [months]	7.09[a] ±1.00	7.10[a] ±0.99	7.32[b] ±0.95	7.29[b] ±0.96	7.08[a] ±1.00	6.02[c] ±0.19	6.00[c] ±0.00
P-enriched soils [Share of farms]	0.55[a]	0.69[b]	0.98[c]	1.00[d]	1.00[c,d]	1.00[c,d]	1.00[b,c,d]
Low-emission manure application techniques [Share of farms}	0.86[a]	0.05[b]	0.43[c,d]	0.53[c]	0.38[d,e]	0.28[e,f]	0[b,f]

Dairy farms

Compliance cost group [cent (kg ECM)$^{-1}$]	0	0-0.3	0.3-0-5	0.5-0.9	-	-	-
Stocking Density [LU ha^{-1}]	1.68[a] ±0.58	2.13[b] ±1.11	2.19[c] ±1.04	1.78[a] ±0.96	-	-	-
Land [ha]	78.98[a] ±48.57	65.09[b] ±38.33	60.74[c] ±35.08	57.99[d] ±35.97	-	-	-
Grassland [Share of land]	0.51[a] ±0.29	0.36[b] ±0.20	0.64[c] ±0.20	0.94[d] ±0.15	-	-	-
Manure Storage [months]	7.18[a] ±0.98	7.01[b] ±1.00	7.07[b] ±1.00	6.99[b] ±1.00	-	-	-
P-enriched soils [Share of farms]	0.46[a]	0.56[b]	0.62[c]	0.55[b]	-	-	-
Low-emission manure application techniques [Share of farms]	0.99[a]	0.26[b]	0.04[c]	0.00[d]	-	-	-

Source: own calculation and illustration; mean value for farm characteristics if not indicated otherwise; Significant differences between groups are indicated with unlike characters within a row. All groups showing not the same character have different means or shares at a significance level of p<0.05. For continuous variables, the Kruskal-Wallis test and, as post-hoc test, the Dunn's Test are applied. For categorical variables, the Fisher's exact test of independence is applied. Characters are derived from the test results using the R package 'rcompanion' 2.0.0; ± - standard deviation; € - Euro; ECM - energy-corrected milk; LU - livestock units; P - phosphorus

5.4.2 Sensitivity to exogenous variables and assumptions

The statistical meta-model shows the impact of prices and crucial assumptions on the compliance costs with the FO 2017 (see Appendix 5.A for detailed description of results). Output prices have an increasing effect on compliance costs as farms may adapt to the FO 2017 by reducing stocking density. Manure export costs drive compliance costs for pig farms as manure export is a core compliance strategy to fulfill the stricter P_2O_5 surplus threshold. For dairy and pig farms, higher costs for low-emission manure application rise compliance costs significantly as the obligatory use of these technologies under the FO 2017 is a main cost driver.

Assumptions on the minimum necessary chemical fertilizer also impact compliance costs with the FO 2017. They influence the N and P_2O_5 surpluses of farms and, hence, the needed effort to meet the nutrient surplus restrictions. Thus, compliance costs increase when a higher minimum chemical fertilizer need is assumed. Accounting for higher MFE than prescribed by the FO lowers compliance costs for pig farms. Pig farms which have to adapt to the stricter P_2O_5 surplus threshold comply by exporting manure. With the exported P_2O_5, N leaves the farm likewise which is required for plant nutrition and needs to be replaced by costly chemical N fertilizer. Accounting for higher MFE for N reduces the chemical N needed to replace the exported manure N and, hence, lowers compliance costs.

5.5 Discussion

5.5.1 Results

We find compliance costs ranging from 0 to 2.66 € pig^{-1} and from 0 to 0.83 ct (kg ECM)$^{-1}$ for pig and dairy farms, respectively. Relating the costs to the standard gross margin, defined as the standardised value of gross production minus special variable costs (European Commission 1985, p. 2) and selected costs, gives insights into the economic impact on farms. The standard gross margins in Germany for 2016/17 were specified as 27.20 € pig^{-1} and 17.94 ct (kg ECM)$^{-1}$. Major variable costs are feeding costs with 67.20 € pig^{-1} and 10.07 ct (kg ECM)$^{-1}$ for pig and dairy farms, respectively. Other relevant cost items are piglets with 65.20 € pig^{-1} or replacements for the dairy herd with 3.60 ct (kg ECM)$^{-1}$ (KTBL 2018b). The figures show that compliance costs with the FO 2017 are small compared to other cost items. Still, farms facing high compliance costs lose a considerable share of their standard gross margin. Taking into account that some of these farms will need to cover e.g. rents or wages from the gross margin, the impact on the farmer's income can be much higher. Furthermore, our analysis may underestimate compliance cost, on one hand due to methodological reasons (Section 5.5.2, 5.5.3), and on the other hand for neglecting possible additional costs caused by the FO 2017. They may be induced by transaction costs which for instance occur in order to find farms willing to import manure or to compose the required fertilizer records. Besides, our analysis focuses on the most important measures of the FO and neglects measures which are for instance linked to weather and location, such as minimum distances for fertilizer application to surface waters.

We do not directly estimate income changes as farm income highly depends on farm characteristics such as interest burden or legal structure which are not accessible in enough detail for our analysis. Karl & Noleppa (2017) quantify the costs related to the FO 2017 in a top down approach and find costs of 2.90 and 4.62 € pig^{-1} for two average German farms (see Appendix 5.I for calculation). A static cost calculation and further methodological differences, as well as the absence of compliance strategies, increase compliance costs compared to the study at hand. Furthermore, Karl & Noleppa (2017, pp. 2ff.) link aggregated costs at the country level to the land area of average farms. This does not give insights on compliance costs at farm-level under farm heterogeneity and the cost driving farm characteristics which the study at hand assesses. Menghi *et al.* (2015) quantify the compliance costs with the Nitrates Directive for typical farms in the EU. They find costs in the ranges of 0 to 1.05 € pig^{-1} (see Appendix 5.J for calculation) and 0.02 to 0.67 ct $(kg\ ECM)^{-1}$ which are similar to our results. We estimated higher costs as measures such as the instruction of low-emission manure application techniques and the limitation of the P_2O_5 surplus, which drive compliance costs in our analysis, are not covered by Menghi *et al.* (2015). Furthermore, high costs only occur for a small share of farms in our analysis which are not subject to research when using a typical farm approach.

Within the legislative process of the FO revision in 2017, the annual costs for the agricultural sector are estimated at 112 million € and additional manure storage is found to be the major cost driver. Stricter P_2O_5 surplus and low-emission manure application techniques are identified as minor drivers (BMEL 2017b, pp. 70ff.). These results differ from our findings as lower costs for meeting the P_2O_5 surplus and little additional costs for low-emission application techniques are assumed. In contrast, higher and fixed costs for additional manure storage enter the calculation of BMEL (2017b, p. 77) which do not reflect scale effects. Aggregated cost calculation for the Dutch implementation of the Nitrates Directive confirm the role of manure transport, induced by strict nutrient application limits, as a major cost driver (van Grinsven *et al.* 2016, p. 80). Research on the outdated Dutch Mineral Accounting System (MINAS), putting a tax on nutrient surpluses, highlights the potential of increased productivity to lower compliance costs (Berentsen 2003, pp. 187ff.) which we do not consider. Productivity changes realize less nutrient excretion at constant production output and therefore, lower nutrient surpluses and the need to adapt to the FO.

5.5.2 Methodological approach

The use of LHS to derive a representative farm sample is advantageous compared to other sampling approaches such as Monte Carlo simulation or selecting a random sample of farms from observed populations. LHS is based on a stratified random sampling approach which ensures that the multi-variate distribution is always approximately covered. A simple Monte-Carlo approach is not stratified and thus would require a far larger number of draws to achieve a similar balanced coverage. The same holds for a non-stratified random sample drawn from the observed population. However, the latter is impossible when using the FSS as in our application, due to data protection requirements.

Compared to approaches which only consider some selected changes in farm management, e.g. assuming unchanged herd sizes and feed management, a farm-scale optimization model such as FarmDyn considers many on-farm compliance strategies and chooses the optimal combination. Therefore, the estimated compliance costs are likely more realistic. This comes at the price of a more complex model which also implies more (uncertain) parameters. Furthermore, our analysis excludes technical progress, for example innovative manure processing, which may lower the compliance costs in the future.

FarmDyn assumes profit maximizing behavior of farmers following standard economic assumptions. This is also reflected in the assumed fertilizer management of farms with high MFE for manure N and minimal use of chemical N and P_2O_5 fertilizer. The statistical meta-model shows that compliance costs are sensitive to assumptions on these parameters. Osterburg & Techen (2012, p. 195) as well as LWK NRW (2018, p. 44) report high differences in fertilizer use between farms, based on non-representative single farm data on nutrient surpluses and fertilizer inputs. When such data on fertilizer use is available for a representative sample, it can be linked to the farm population (Buckley *et al.* 2015) to estimate the distribution of the reduction potential. The results of Osterburg & Techen (2012, p. 195) and LWK NRW (2018, p. 44) show the large potential of reducing fertilizer use on less efficient farms. This reduction may occur in response to the compulsory fertilizing planning under the FO 2017 and might realize cost savings for farms. However, this reaction cannot be depicted by a modelling approach assuming profit maximization, which implies operating on the efficient technical and economic frontier as defined by the model structure and parameters.

Supply-side models like FarmDyn are characterized by exogenous input and output prices. The statistical meta-model gives insights into the influence of prices on compliance costs. Output prices, prices for manure application and manure export costs highly impact compliance costs. However these prices, especially manure export costs, are expected to change due to the FO 2017. For instance, average transport distances and transaction costs will likely increase as more farms are forced to export excess manure. Manure allocation models (van der Straeten *et al.* 2012; Schäfer & Britz 2017) or (partial) equilibrium models (Britz *et al.* 2012) can give insights into manure flows and related export costs or market feedback. These models, however, usually capture technology choice at a lower level of detail than farm models.

5.5.3 Data sources

The use of LHS allows the creation of a farm sample by linking different data sources and thereby, increases information on relevant farm characteristics. While most farm characteristics are covered by the last FSS, some are based on older data or assumptions (Appendix 5.B) and thus cause uncertainty. Firstly, the distribution of manure storage capacity in months is based on data from 2007, as more recent data is not available. Since then, average storage capacities may have increased which could imply an overestimation of compliance costs. However, the potential error is likely small as the statistical meta-model returns only a slight cost reduction if an additional month of storage is already available. That finding reflects that only farms exceeding 3 LU ha^{-1} are subject to a change in the legally required minimum storage capacity. Furthermore, the FSS only contains the share of manure applied with different application techniques but no information on the presence of the technology on the farm. We therefore made the assumption that a certain application share coincides with the presence of the low-emission manure application techniques. This assumption may lead to an underestimation of compliance costs and an overestimation of the share in the farm population without any costs. However, the statistical meta-model gives insight into the sensitivity of compliance costs depending on the available techniques. Furthermore, these uncertainties only impact the distribution of compliance costs but not their estimated range and how they depend on farm characteristics.

Our analysis mainly relies on data from 2016. The discussion on the revision of the FO however, started around 2014. Hence, some farms may have adapted to the upcoming FO beforehand and the changed farm characteristics are captured in the FSS from 2016. This potentially leads to an underestimation of compliance costs, as the adaptations and their costs are not linked to the FO 2017 in our analysis. Furthermore, the FSS records farms which are listed as single legal units. Farms are frequently split into numerous legal units, e.g. for tax optimization, which is not recognizable in agricultural statistics. This potentially leads to an overestimation of compliance costs for instance, stocking density of farms is higher when animal husbandry is separated from the arable farming branch.

5.5.4 Policy implications

Our results indicate that compliance costs are highly heterogeneous and that a major share of farms do not face any costs. This alone is a contribution to the societal discussions around stricter environmental regulations in general, and the FO 2017 more specifically. Our study allows pinpointing farms which are likely to face higher costs, of which some may lose up to 10% of their gross margin. Firstly, that allows for better targeting of policy measures supporting farms to adjust to the new legislation, such as advisory services with regard to adjustment strategies or investment aids into storage facilities. Secondly, it can give guidelines for efficient risk-based control schemes and reasonable levels of fines in case of non-compliance.

Empirical results hint at a lack of compliance with the FO in the past (LWK NRW 2014, pp. 54ff.), although clear scientific evidence is missing. This may increase the costs linked to the introduction of the FO 2017, which also improves enforcement mechanisms. Thus, farmers non-compliant under the FO 2007 might face costs to comply with measures which have already been in place since the FO 2007. That is not captured in our analysis as we assume full compliance both under the FO 2007 and 2017.

Our results indicate that manure application on dairy farms is limited by the manure N application threshold of 170 kg N ha^{-1}. However, there is the possibility to apply for so-called derogation at the European Commission which allows for the application of up to 250 kg N ha^{-1} on intensive grassland. In Germany, the derogation stopped in 2013 and has not yet been reimplemented. Therefore, this measure was excluded from the analysis. Its potential reintroduction would decrease compliance costs on some farms by allowing higher manure application on intensive grassland. Thereby, the cost decrease induced by the derogation largely depends on the detailed design of the measure (van der Straeten *et al.* 2012, p. 99).

We included two feeding regimes for pigs which reduce N and P_2O_5 excretion per animal at unchanged final weight as adjustment strategies to decrease nutrients load. We find strongly reduced N and P feeding to be the most cost-efficient compliance strategy for pig farmers. This is supported by findings from practical feeding experiments in Northwest Germany, which only report very slight cost differences between the two feeding regimes (Stalljohann 2017, pp. 18ff.; Meyer & Vogt 2017, p. 4). However, strongly reduced N and P feeding strategies are so far rarely applied (LWK NRW 2018, p. 25). Potential reasons are insufficient knowledge of farmers or a weak empirical basis related to the impact on animal performance. Policymakers should respond with educational measures and increased research efforts.

5.6 Conclusion

We conclude that the compliance costs with the revised FO 2017, which is implementing the Nitrates Directive in Germany, are highly heterogeneous. They range from 0 to 2.66 € per pig and 0 to 0.83 ct per kg milk. 47.3% of pig and 38.4% of dairy farms do not face any costs. Compliance costs strongly depend on farm characteristics such as stocking density, soil P status or the availability of low-emission manure application techniques. The combination of LHS and a single farm model is a promising approach to assess on-farm compliance costs with environmental regulations under limited data availability. The generic nature of the modelling setup allows its application to other regions as well as other regulations. Future research on current implementations of EU environmental regulations should go beyond the compliance cost perspective and link the economic assessment to the quantification of on-farm emission reduction to estimate abatement costs and the cost efficiency of measures.

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Chapter 6

A life cycle assessment of liquid pig manure transport in line with EU regulations: a case study from Germany[5]

Abstract

The transport of excess manure to crop farming systems is a core measure of livestock farmers to comply with environmental regulations like the EU Nitrates Directive. The German implementation of the directive has recently been revised and will lead to a distinct increase of manure transport. We quantify the environmental impact of 1 m^3 of pig manure excreted in scenarios with and without manure transport by life cycle assessment, focusing on farming systems in North-West Germany. Furthermore, we assess how the environmental impact is linked to the regulation which is causing the transport. Compared to a reference scenario without transport, manure transport lowers all assessed impact categories and no trade-off between environmental impacts is found. Major reductions are realized for global warming (39%), freshwater (61%) and marine eutrophication (54%) as well as particulate matter formation (10%). Furthermore, the depletion of fossil fuels and phosphate is lowered. Reductions are mainly caused by an increase of nutrient use efficiency and the savings in chemical fertilizer. However, in a scenario where manure transport is caused by strict regulations regarding phosphate, needed nitrogen leaves the exporting farm likewise and chemical fertilizer use rises at the exporting farm. Caused by the increased fertilizer use, the positive environmental effect of manure transport diminishes, even leading to a rise of fossil fuel depletion (FFD) by 20% and slight rise of global warming potential by 3%. However, we find that the use of lorries which combine manure and grain transport and, thereby, reduce empty drives, can prevent this trade-off. Our results show the potential of manure transport to reduce the environmental burden caused by the geographical concentration of livestock production. However, the impact of manure transport on global warming and FFD highly depends on the transport distance. Agronomic measures are needed to prevent the increase of chemical N fertilizer use on the exporting farms and policymakers should be aware of possible trade-offs between strict regulations regarding phosphate and FFD.

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6.1 Introduction

In several European countries, intensive livestock production is highly geographically concentrated. Regions with high stocking density are characterized by high nitrogen (N) and phosphorus (P) inputs and surpluses (Grizzetti *et al.* 2007, pp. 80ff.) which increase the risk of uncontrolled nutrient loss to the environment. N and P losses pose a threat to air and water quality, biodiversity, and climate (Sutton *et al.* 2013, pp. 32ff.). In the EU, the Nitrates Directive is the key legislation for lower nitrate (NO_3^-) emissions from agriculture and protects drinking water sources and surface waters (European Council 1991). The implementation of the Nitrates Directive in member states is often linked to measures to reduce P and ammonia (NH_3) losses, needed to fulfil environmental targets laid down in the EU Water Framework Directive (WFD) (European Parliament, European Council 2000) or the EU Directive on the Reduction of National Emissions of Certain Atmospheric Pollutants (European Parliament, European Council 2016).

Mandatory requirements under the above-mentioned directives prescribe maximum amounts of applied nutrients and banning periods for manure application. To comply with these legal requirements, livestock farms can reduce stocking density, rent or buy additional land, or change animal feeding to lower nutrient excretion. Furthermore, manure transport is a major adaption measure of livestock producers to fulfil requirements with regard to nutrient application. The transport leads, following the logic behind the Nitrates Directive, to a reduction of NO_3^- losses on the manure exporting farm. However, manure transport impacts on numerous emission sources on the manure exporting and importing farm. In addition, transport itself is linked to emissions and may lead, for instance, to a negative net impact on global warming or the formation of particulate matter. Life cycle assessment (LCA) quantifies the effect of manure transport on numerous environmental impact categories, includes all potentially affected emission sources and, hence, assesses the environmental effect comprehensively. This allows detecting possible trade-offs or combined benefits of manure transport with other environmental targets, induced by measures to protect ground and surface waters.

In Germany, livestock production is clustered in the Northwest. In this area, high amounts of manure are already transported intraregionally between farms under the current legal framework; e.g. in Lower Saxony the share lies around 6% of the total manure and biogas digestate production of 59 m t in 2015/16 (LWK Nds. 2017, pp. 18, 44). Transport is triggered by restrictions put in place by the Fertilization Ordinance (FO) (BMEL 2017) which mainly implements the Nitrates Directive in Germany and also comprises measures targeting P and NH_3 emissions. A revised FO entered into force in June 2017 and includes considerably tighter mandatory requirements (Chapter 2). Hence, a further increase of manure transport is likely (LWK Nds. 2017, pp. 26ff.). First estimates for Lower-Saxony predict that around 7% of total livestock manure is affected by stricter maximum nutrient application rates (Osterburg & Techen 2012, p. 213) and will potentially be transported. Therefore, the integrated assessment of the environmental impact of manure transport is of recent interest.

Several LCA studies examine the management of excess manure in livestock production systems, including the use of manure processing techniques (McAuliffe *et al.* 2016, pp. 17ff.). Manure importing farms are able to reduce chemical fertilizer use which is associated with emission reduction (Prapaspongsa *et al.* 2010, pp. 1414ff.; Brockmann *et al.* 2014, p. 276). On the other hand, transport itself is related to carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions (Lopez-Ridaura *et al.* 2009, pp. 1301f.; De Vries *et al.* 2013, p. 1592). Different manure processing techniques are able to reduce the ratio between nutrients and volume and, hence, decrease transport emissions per unit of nutrient. However, the processing is partly linked to direct emissions and to additional costs (Willeghems *et al.* 2016, pp. 15ff.; De Vries *et al.* 2012, pp. 179ff.). Furthermore, the environmental impact of manure transport and processing depends on the regulatory regimes on nutrient application (Hoeve *et al.* 2016, pp. 713ff.). We contribute a case study on manure transport in Germany to existing research and explicitly include the impact of the regulation which causes manure transport.

Depending on the regulations triggering manure export, one of two scenarios applies: First, livestock farms are often characterized by inefficient nutrient management, leading to high N and phosphate (P_2O_5) surpluses (Osterburg *et al.* 2004, pp. 16ff.; Osterburg & Techen 2012, pp. 187ff.). In this case, exported manure does not have to be replaced with chemical fertilizer to sustain nutrient need of crops. The nutrient use efficiency, understood as the relation between nutrient input and output, increases as the total amount of applied nutrient is lowered, but crop output stays constant. Second, the exporting farms may have to substitute exported nutrients with chemical fertilizer to sustain nutrient demand by crops. This generally can be caused by direct thresholds for manure N application as prescribed in Annex III of the Nitrates Directive. Furthermore, restrictions for one nutrient can limit the application of another nutrient as they are combined in manure. The N:P_2O_5 ratio in manure is generally lower than 2:1 whereas plant needs reflect on average a ratio over 2.5:1 (Schröder 2005, p. 257). This ratio is even worsened by a comparatively low nutrient use efficiency of manure N compared to manure P_2O_5. It implies an over application of P_2O_5 when a high share of plant N needs are met with manure (De Vries *et al.* 2015, pp. 93ff.). Hence, strict thresholds with regard to P_2O_5 limit the use of manure N at the same time. This is the case for the FO 2017 which comprises very strict measures with regard to the application of P_2O_5 and can cause an increase of the chemical N need on the importing farm. The described scenarios most likely influence the environmental impact of manure transport and, therefore, need to be taken into account in its assessment.

The objective of our study is to quantify the environmental effect of liquid pig manure transport by lorry from a livestock to an arable farm, compared to a situation without transport using LCA. Furthermore, we explicitly assess the impact of different manure application thresholds in environmental legislation which can cause manure transport. We develop our scenarios for triggers of manure transport based on the current revision of the FO in Germany and, thereby, provide an analysis of a recent policy change.

6.2 Material and methods

6.2.1 LCA approach and functional unit

LCA is a methodology to quantify the emissions and resource consumption of a product along its whole life cycle, standardized by international norms (ISO 2006a; 2006b). In this study, the environmental consequences of changing from a management without to a management with manure transport are assessed. To do so, we take all relevant emission sources and resource needs along the life cycle of manure into account and relate them to the functional unit of $1m^3$ of pig manure excreted.

6.2.2 System characterization and scenarios

System boundaries are starting from manure entering the subfloor storage on the exporting farm to the crop production stage, and include changes in the chemical fertilizer use. Assumptions regarding manure composition and storage are equal in all scenarios. Manure is excreted by pigs with a nutrient content of 8 kg N m^3 and 2.93 kg P_2O_5 m^3 (Table 6.1), representing excretion rates based on N and P reduced feeding strategies (BMEL 2017, p. 18), which are commonly applied in Germany. Manure is stored in-house under fully slatted floor for 4 months and in a slurry tank with a natural crust cover for 5 more months. We assume that the manure storage is emptied completely in May and then filled up evenly. There is no scrubber system in place to reduce NH_3 and particulate matter emissions from housing. Four scenarios are defined:

- Reference (Ref): Manure is stored and applied at the exporting farm by trailing hose. Manure nutrients do not replace chemical N or P_2O_5 fertilizer.
- Reference and replace N (RefN): Manure is stored and applied at the exporting farm by trailing hose. Manure N replaces chemical N fertilizer.
- Transport (Trans): Manure is stored on the exporting farm, transported by lorry to the importing farm and applied by trailing hose. Manure nutrients replace chemical N and P_2O_5 fertilizer.

- Transport and improved technology (TransTech): Manure is stored on the exporting farm and transported to the importing farm by a lorry which combines manure and cereal transport. At the importing farm, it is applied by injection and replaces chemical N and P_2O_5 fertilizer.

In this study, the environmental impact of manure transport under the FO 2007 (BMELV 2007) is represented by the comparison of the scenarios Ref and Trans. The impact of manure transport under the FO 2017 is represented by the comparison of the scenarios RefN and Trans as well as RefN and TransTech.

In the scenarios without transport (Ref, RefN), manure is applied in spring to maize using trailing hose technology. We include emissions from diesel for machinery use for the transport from the farm buildings to the field, in the following referred to as on-farm transport, and the application of manure and chemical fertilizer. To calculate the diesel need, we assume a distance between farm and field of 5 km, field size of 2 ha, and working width of 24 m, 36 m and 24 m for trailing hose, chemical N and chemical P_2O_5 fertilizer spreader, respectively (KTBL 2018). The regulations triggering manure transport (Chapter 4, 5) are represented in the assumptions on the replacement of chemical fertilizer with manure nutrients which strongly influence LCA results (Hanserud *et al.* 2018). In Ref, mineral fertilizer equivalents (MFE) of 0 are assumed as manure does not replace any chemical fertilizer. In RefN, the MFE are 70% of N in manure, defined by the compulsory fertilizing planning of the FO 2017 (Section 6.2.3). Storage and stable losses have been subtracted from animal excretion based on a standard loss factor of 70%, leading to the accounting of 49% of the excreted N. MFE of P are 100%.

The transport scenarios (Trans, TransTech) differ in the used transport and manure spreading technologies. In Trans, manure transport is realized by lorry with an actual load of 24 t and a utilization of 50% to include emissions from returning empty. Manure is transported as unprocessed, liquid manure over 75 km, representing the upper limit of distances between exporting and importing regions in North-West Germany (LWK NRW 2014, pp. 118ff.). In TransTech, manure transport is realized by semi-trailer with a built in tank for manure. This allows transporting manure from the livestock to the arable production regions and cereals on the way back, reducing the transport emissions by avoiding empty trips. The actual load is 23.5 t, corresponding to a manure load of 26 m^3 and around 50 m^3 of cereals (Bensing 2013, p. 79).

On the importing farm, manure is not stored and transported directly to the field which avoids on-farm transport compared to the scenarios without transport. In Trans, manure is applied to winter wheat using trailing hose. In TransTech, manure is applied to maize using injection with a working width of 6 m. Assumptions with regard to field size and technology for chemical fertilizer application are equal in all scenarios. In line with the compulsory fertilizing planning of the FO 2017, MFE for manure N are 70% and for P_2O_5 100% (Section 6.2.3).

Table 6.1 Mass balance flow at the storage and application stage for all scenarios

	Ntot	TAN	Norg	P_2O_5
After excretion	8.00	5.60	2.40	2.93
After stable and storage	5.98	3.63	2.35	2.93

Source: own calculation and illustration; Ntot - total nitrogen; TAN - total ammonia nitrogen; Norg - organic nitrogen; P_2O_5 - phospate

6.2.3 Manure transport under the FO 2007 and FO 2017

The purpose of the following paragraph is to show how the measures of the FO are linked to the fertilizer management of farms and can lead to the increase of chemical N need when manure is exported, as stated in the introduction. To do so, we specify the fertilizer management in line with the FO 2007 and FO 2017 for 1 ha on a manure exporting livestock farm. We assume a stocking density of 3.5 livestock units (LU) ha^{-1} which is in the range of typical pig farms in Northwest Germany (Budde 2013, p. 89). This corresponds to manure excretions of 280.0 kg N ha^{-1} and 102.6 kg P_2O_5 ha^{-1}. We assume the cultivation of maize and that soils are highly P-enriched (in accordance with FO defined as >0.0002% P_2O_5 in soil applying the calcium-acetate-lactate method) which is common for regions with high pig stocks in Northwest Germany (Osterburg & Techen 2012, pp. 200f.). To represent actual farming practice, chemical starter fertilizer is applied to maize, including 20 kg P_2O_5 ha^{-1} (LWK NRW 2014, p. 55).

The fertilizer use of the prescribed management (Table 6.2) is based on the compulsory fertilizing planning under the FO 2017. Depending on the yield level, the needed amount of fertilizer application is calculated and supply from other sources, such as delivery from the soil pool, needs to be taken into account (see Section 2.2.1 for detailed explanation). Furthermore, the fertilizing planning defines MFE, leading to the accounting of 100% for P_2O_5 and 70% of N (stable and storage losses already subtracted).

In the FO 2007 and FO 2017, the threshold for manure N application and the limitation of the N and P_2O_5 surplus generally restricts the use of manure. Precise calculation schemes and input parameters are provided by the FO and by organizations at the regional level (LWK NRW 2015). The manure application threshold is calculated from animal N excretion minus barn and storage losses. Under the FO 2007 and FO 2017, the threshold is 170 kg N ha^{-1}. Furthermore, farms have to calculate N and P_2O_5 balances. Nutrient removal with the harvested product is offset against nutrient input by chemical fertilizer and manure. Under the FO 2007, N balance surplus is limited to 60 kg ha^{-1} and the P_2O_5 surplus to 20 kg ha^{-1}. Under the FO 2017, the allowed N and P_2O_5 surplus are reduced to 50 and 10 kg ha^{-1}, respectively. Furthermore, there is no P_2O_5 surplus allowed on highly P-enriched soils.

In the fictitious scenario without any regulation, the same amount of chemical fertilizer is applied as in scenario FO 2007 and additional manure is applied over plant need. The resulting nutrient surpluses, shown in Table 6.2, are in the range of empirical results for livestock-producing farms in Germany (Osterburg & Techen 2012, pp. 187f.). Under the FO 2007, the application of manure is limited by the restriction of the P surplus to 20 kg ha^{-1}. To fulfil the requirements, the livestock farm has to export 5.8 m^3 ha^{-1} compared to a situation without legislation. As the manure does not need to be replaced by chemical fertilizer to sustain crop N need, the nutrient use efficiency on the exporting farm increases. In the developed LCA scenarios, this is represented by the comparison between Ref (manure nutrients do not replace any chemical fertilizer on exporting farm) and the transport scenarios. Under the FO 2017, additional manure transport is triggered by the ban of any P_2O_5 surplus. In this case, 6.8 m^3 ha^{-1} of manure are exported additionally and N needed for plant nutrition leaves the farm as P_2O_5 and N are combined in manure. Hence, to sustain plant N need and compensate for the exported manure N, the chemical N fertilizer need increases by 26.8 kg ha^{-1}. This increase is calculated based on the compulsory fertilizing planning under the FO 2017 and, therefore, in line with legal requirements. In the LCA, this is represented by comparing the scenario RefN (manure N replaces chemical N fertilizer on the exporting farm) and the transport scenarios.

Table 6.2 Nutrient thresholds calculation in situation without regulation, under Fertilization Ordinance 2007 and under Fertilization Ordinance 2017 on a manure exporting farm

	No regulation	FO 2007	FO 2017
Manure N excretion per ha [a] (kg ha^{-1})	280	233.4	178.8
Manure P_2O_5 excretion per ha [a] (kg ha^{-1})	102.6	85.5	65.5
Chemical N applied per ha (kg ha^{-1})	55.6	55.6	82.4
Chemical P_2O_5 applied per ha (kg ha^{-1})	20.0	20.0	20.0
Manure N threshold per ha [b] (kg ha^{-1})	196.0	163.4	125.2
N surplus per ha [c, d] (kg ha^{-1})	49.1	16.5	5.1
P_2O_5 surplus per ha [d] (kg ha^{-1})	37.1	20	0
Manure export (m^3 ha^{-1})	-	5.8	5.8 + 6.8

Source: own calculation and illustration; [a] gross N and P_2O_5 from animal excretion which enters threshold calculations; [b] net N excretion according to the Fertilization Ordinance, stable and storage losses have been subtracted from manure N; [c] net surplus according to the Fertilization Ordinance, stable, storage and application losses have been subtracted from manure N; [d] removal with harvested maize of 202.5 kg N ha^{-1} and 85.5 kg P_2O_5 ha^{-1} enters surplus calculation; FO - Fertilization Ordinance; N - nitrogen, P_2O_5 - phosphate

6.2.4 Environmental impact calculation

The emissions of NH_3, N_2O, NO_x, dinitrogen (N_2), NO_3^-, methane (CH_4), CO_2, and orthophosphate (PO_4) as well as resource depletion are calculated. With regard to different N emissions, we apply a mass flow approach, meaning a loss of N in one stage of the life cycle reduces the amount of N entering the next stage. N_2 is not related to environmental impacts but needs to be quantified to determine the amount of total N at different stages. The calculation schemes for NH_3 emissions from storage, NO_3^- losses, and PO_4 losses require assumptions linked to the farm location, as for instance weather or soil type, which are equal in all scenarios.

NH_3 emissions from housing are calculated using a fixed emission factor (EF) of 0.3 of total ammonia nitrogen (TAN) from Dämmgen *et al.* (2010, p. 245). NH_3 emissions from outside storage are modeled based on Rigolot *et al.* (2010, pp. 1415ff.) as a function of storage time, surface area, and temperature. Surface area per m^3 of manure depends on the filling level of the storage. Annual average temperature in Northwest Germany is 10.4° Celsius (DWD 2016). CH_4 emissions from housing and outside storage are calculated based on Sommer *et al.* (2004, p. 145) as a function of volatile solids (VS) in manure, temperature, and storage time. Manure contains 64 kg VS m^{-3}, the value is calculated based on annual VS excretions (Dämmgen *et al.* 2011, p. 125). N_2O, N_2 and NO_x emissions from housing and storage are quantified by annual EF from Rösemann *et al.* (2017, p. 187), being 0.005, 0.015, and 0.0005 of total N, respectively. We do not take any NO_3^- leaching and P losses from stable and storage into account as it is prevented by closed chambers or manure cellars.

Different emissions occur during the application of chemical fertilizer and manure. We apply an NH_3 EF of 0.13 of TAN for manure spreading by trailing hose (Döhler *et al.* 2002, p. 73) and 0.025 by injection (Rösemann *et al.* 2015, p. 183). For chemical fertilizer, an NH_3 EF of 0.022 of total N is used (EEA 2013a, p. 14). We apply the same EF for N_2O, NO_x, and N_2 losses from manure and chemical fertilizer at field level. EF are 0.01 (IPCC 2006a, p. 11.11), 0.012, and 0.07 (Rösemann *et al.* 2017, p. 329) of total N, respectively.

NO_3^- leaching is quantified using a calculation scheme developed by Brentrup *et al.* (2000): N surplus is calculated, including deposition, mineralization, and fertilizing as input and plant removal and demineralization as output. Depending on weather and soil qualities, a share of surplus N leaches as NO_3^-. Average N deposition in Germany is 17.5 kg ha^{-1} (Kruit *et al.* 2014, p. 102). Soil texture, needed to estimate the field capacity in the effective rooting zone, was estimated as loamy sand (Roßberg *et al.* 2007, pp. 27ff.). Average precipitation rate in Northwest Germany, which is needed to calculate leached water quantities, is 432 mm in summer and 384 mm in winter (DWD 2017).

To quantify P emissions, we apply the model SALCA P (Prasuhn 2006). It takes P losses from soil erosion, leaching and runoff into account which are converted to PO_4 to estimate the environmental impact. Losses via soil erosion are calculated based on the amount of soil eroded, the P content of the top soil, and the share of eroded soil that reaches surface waters. We use default values of 0.2 for the share reaching surface water and a soil content of 0.95 g P kg^{-1} (Prasuhn 2006, p. 3). Based on Bosco *et al.* (2015, p. 238), we assume an annual erosion of 3 t ha^{-1}. A small share of P leaches to the ground water. We adopt a default value of 0.7 kg ha^{-1} and assume that there is no additional risk due to the soil type. Following SALCA P, we include correction factors based on the amount of slurry applied (between 1 and 1.3) and the level of plant available P. On the exporting farm, highly P-enriched soils correspond to a correction factor of 1.4 (represents class E in German P soil classification system). On the importing farm, a balanced P level is assumed (represents class C in German P soil classification system), corresponding to no correction (factor 1) (Prasuhn 2006, pp. 4ff.). Furthermore, P which is not bound to soil particles runs off to surface waters. A default value of 0.175 for P runoff is adopted and a correction factor is used based on manure and chemical fertilizer application, reaching from 1.6 to 2.0. In addition, a correction factor for the level of plant available P is included and additional risk due to soil type or topography is excluded (Prasuhn 2006, pp. 9ff.). We assume that fields have no drainage and, therefore, do not take this loss pathway into account.

Indirect N_2O emissions following the deposition of NH_3 and NO_x and the leaching of NO_3^- are included at all relevant stages with EF of 0.01 and 0.0075, respectively (IPCC 2006a, p. 11.24). External processes consist of chemical N and P_2O_5 fertilizer production, lorry transport, and diesel provision and combustion for on-farm machinery use. Data for EF and resource depletion is taken from the LCA database ProBas and EEA (2013b), summarized in Table 6.3.

Table 6.3 Emission factors for external processes

	CO_2 [kg]	CH_4 [kg]	N_2O [kg]	NH_3 [kg]	NO_x [kg]	SO_2 [kg]	PM10 [kg]	Gas [MJ]	Oil [MJ]	Coal [MJ]
Lorry transport [a] (t km)	0.099	$4E^{-5}$	$3E^{-6}$	$4E^{-7}$	0.001	$1.8E^{-4}$	$7E^{-6}$	0.03	1.250	0.073
Chemical N fertilizer [a] (kg N in fertilizer)	2.960	0.006	0.015	0.007	0.016	0.005		37.4	8.950	4.105
Chemical P_2O_5 fertilizer [a] (kg P_2O_5 in fertilizer)	1.200	0.002	$6E^{-5}$	$1E^{-5}$	0.010	0.012		5.94	8.070	2.770
Diesel provision [a] (l)	0.416	0.001	$2.3E^{-4}$	0.001	0.001	0.001	2E-4	1.074	36.874	0.519
Diesel combustion [b] (l)	2.639		0.000	0.000	0.014		0.001			

[a] LCA database ProBas, except PM10 for lorry transport from UBA (2016); [b] EEA (2013b, p.24); CH_4 - methane; CO_2 - carbon dioxide; N_2O - nitrous oxide; NH_3 - ammonia; NO_x - nitrogen oxides; PM10 - particulates; SO_2 - sulfur dioxide

6.2.5 Impact assessment

Resource use and emissions are related to the corresponding impact categories. To do so, different pollutants and resource use are converted to equivalents (eq) of the relevant impacts. We adapt conversion factors from ReCiPe v.1.08 at midpoint level (Goedkoop *et al.* 2013, Appendix 6.A). P depletion is expressed as kg P_2O_5 in fertilizer used.

6.2.6 Sensitivity Analysis

We conduct a sensitivity analysis to examine the influence of changes in crucial parameters (Table 6.4). Thereby, we focus on factors and calculation schemes for different emissions as well as on selected assumptions regarding the management. Low and high values are deployed for the varied parameters, based on literature values whenever possible. We restrict the presented results to the most influential parameters, leading to a more than 20% change compared to the basic results, and focus on possible changes in the ranking of the scenarios.

Table 6.4 Overview of varied parameters in the sensitivity analysis

Parameter	Basic value	High value	Low value
EF Lorry transport			
[kg CO_2 tkm^{-1}]	0.099[a]	0.124[b]	0.074[b]
[kg PM10 tkm^{-1}]	0.000007[a]	0.000009[b]	0.000005[b]
[kg FFD tkm^{-1}]	0.031[a]	0.039[b]	0.023[b]
EF Chemical N fertilizer production.			
[kg CO_2 (kg N)$^{-1}$]	2.96[a]	3.70[b]	2.22[b]
[kg FFD (kg N)$^{-1}$]	1.08[a]	1.35[b]	0.81[b]
EF NH_3 stable & storage			
[share of TAN]	0.33[c]	0.40[d]	0.24[d]
EF CH_4 storage			
[kg CH_4 m^{-3} manure]	1.98[c]	2.57[e]	1.39[e]
EF N_2O field			
[share of total N applied]	0.01[c]	0.03[f]	0.003[f]
EF Indirect N_2O following leaching			
[share of total N leached]	0.0075[c]	0.025[f]	0.0005[f]
EF NH_3 manure application			
trailing hose [share of TAN]	0.13[c]	0.15[d]	0.11[d]
injection [share of TAN]	0.025[c]	0.029[d]	0.021[d]
P loss			
Soil erosion [t ha^{-1} a^{-1}]	3[c]	20[g]	0.5[g]
Reaching surface [share of eroded soil]	0.2[c]	1	0
Topography risk factor	1[c]	1.2[h]	0.8[h]
On-farm transport distance			
[km]	5[i]	30[l]	1[l]
Transport distance			
[km]	75[i]	250	30

[a] see table Table 6.3; [b] variation of 25% from basic value; [c] see Section 6.2.4; [d] Rösemann et al. (2017, p. 135), EMEP (2007, p. 19); [e] IPCC (2006b, p. 10.48); [f] IPCC (2006a, pp. 11.11, 11.24); [g] Bosco et al. (2015, p. 238); [h] Prasuhn (2006, p. 10); [i] see Section 6.2.2; [l] KTBL (2018); CH_4 - methane; CO_2 - carbon dioxide; EF - Emission factor; FFD - Fossil fuel depletion; N - nitrogen; N_2O - nitrous oxide; NH_3 - ammonia; P - phosphorus; PM10 - particulates; TAN - total ammonia nitrogen

6.3 Results

6.3.1 Global warming potential

CH_4 emissions from storage and direct N_2O emissions following manure and chemical fertilizer application dominate the global warming potential (GWP) in all scenarios (Figure 6.1). CO_2 emissions from the use of diesel for machinery used to apply manure and fertilizer, being part of the application stage, contribute only a minor share in all scenarios, for instance 1.01% of total GWP per m^3 in the reference scenario without transport (Ref). In the transport scenario with improved technology (TransTech), emissions from lorry transport are almost halved by the use of lorries combining manure and grain transport. However, the effect on total GWP is small as transport emissions are a minor share of the total GWP in the two scenarios with transport.

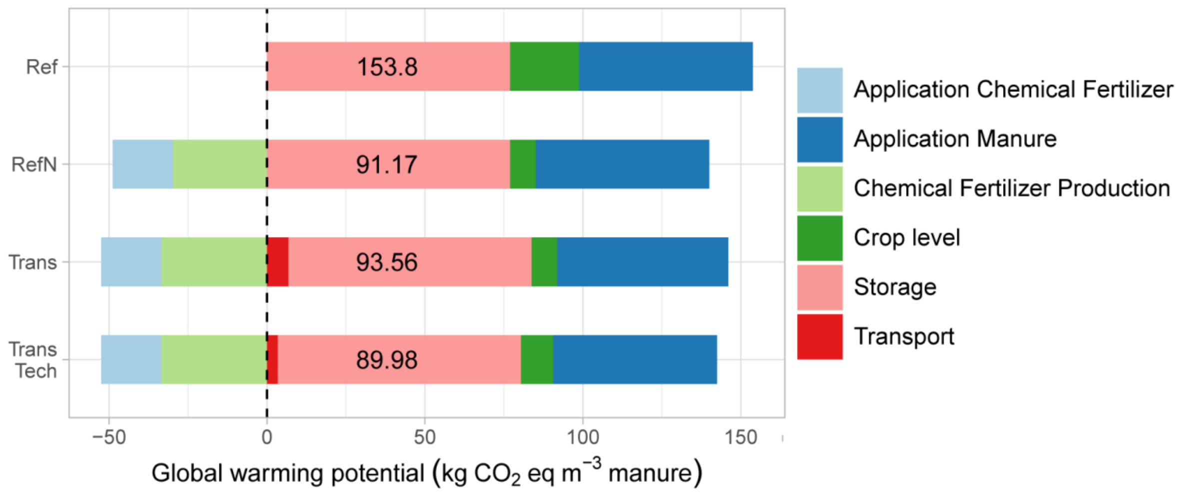

Figure 6.1 Global warming potential for the assessed scenarios, divided into stages

Source: own calculation and illustration; numbers on the bars are the net-impact; CO_2eq - carbon dioxide equivalent

GWP is 39.17% lower in the transport scenario (Trans) compared to Ref, representing manure transport induced by the FO 2007 (Table 6.5). The reduction is realized by the replacement of chemical fertilizer on the importing farm by manure N and P, and the reduction of the related emissions from the provision of chemical fertilizer (33.49 kg CO_2eq m^{-3}). This overcompensates CO_2 emissions from transport by lorry (6.83 kg CO_2eq m^{-3}). Furthermore, the lower total N input leads to a reduction of direct and indirect N_2O losses in Trans (8.14 kg CO2eq m^{-3}) compared to Ref (21.90 kg CO_2eq m^{-3}). Comparing the reference and replace N scenario (RefN) and Trans, represents manure transport induced by the FO 2017. The GWP is 2.62% higher in Trans than in RefN. The slight increase is caused by the replacement of manure N with chemical N in RefN and, therefore, transport does not lead to a net decrease of chemical fertilizer use as under the FO 2007. However, the use of lorries combining manure and grain transport can outweigh this increase.

Table 6.5 Environmental impacts in the scenarios and comparison of different scenarios

	GWP	TA	FE	ME	PMF	FFD	P depl.
Ref	153.80	6.78	0.01	1.69	0.93	0.42	0.00
RefN	91.17	6.32	0.01	0.77	0.84	-3.84	0.00
Trans	93.56	6.30	0.00	0.77	0.84	-3.07	-2.93
TransText	89.98	4.63	0.00	0.85	0.62	-4.01	-2.93
Comparison of Ref and Trans, representing manure transport under the FO 2007							
	-60.24 (-39.17%)	- 0.47 (-6.99%)	-0.01 (-60.92%)	-0.92 (-54.37%)	-0.09 (-10.05%)	-3.48 (-835.8%)	-2.93
Comparison of Ref N and Trans, representing manure transport under the FO 17							
	2.39 (2.62%)	-0.01 (-0.20%)	-0.01 (-60.92%)	0.00 (0.09%)	0.00 (-0.03%)	0.77 (-20.08%)	-2.93
Comparison of Ref N and TransTech, representing manure transport under the FO 2017							
	-1.19 (-1.31%)	-1.69 (-26.75%)	-0.01 (-60.92%)	0.08 (9.86%)	-0.22 (-26.57%)	-0.18 (4.59%)	-2.93

Source: own calculation and illustration; Ref - reference scenario without transport; RefN - reference scenario without transport and the replacement of chemical N fertilizer; Trans - transport scenario; TransTech - transport scenario with improved technology; FO - Fertilization Ordinance; GWP - global warming potential; TA - terrestrial acidification; FE - freshwater eutrophication; ME - marine eutrophication; PMF - particulate matter formation; FFD - fossil fuel depletion; P depl. - phosphorus depletion

6.3.2 Terrestrial acidification

Terrestrial acidification (TA) is dominated by NH_3 emissions from manure storage and manure application (Figure 6.2). Sulfur dioxide (SO_2), NO_x and NH_3 emissions from chemical fertilizer production and application as well as from transport are only minor sources. TA is 6.99% lower in Trans compared to Ref. The reduction is achieved through the savings in chemical fertilizer production and application (0.51 kg SO_2eq m^{-3}) which compensates a slight increase of NO_x and SO_2 emissions from transport (0.04 kg SO_2eq m^{-3}). However, the above-mentioned main emission sources are equal in both scenarios and, therefore, no larger changes occur. TA decreases only slightly by 0.20% in Trans compared to the RefN which already included lower emissions due to manure N replacing chemical N fertilizer (Table 6.5). However, in TransTech, TA is reduced by 26.75% compared to RefN. This is caused by the use of injection instead of trailing hose and illustrates that the use of manure application with lower NH_3 emissions clearly compensates slight increases of TA due to transport emissions.

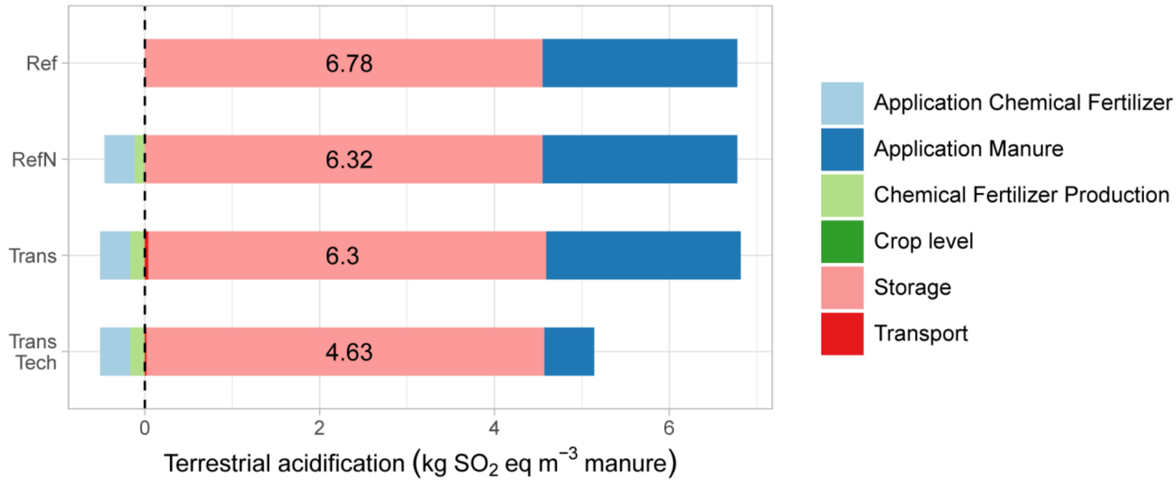

Figure 6.2 Terrestrial acidification for the assessed scenarios, divided into stages

Source: own calculation and illustration; numbers on the bars are the net-impact; SO_2eq - sulfur dioxide equivalents

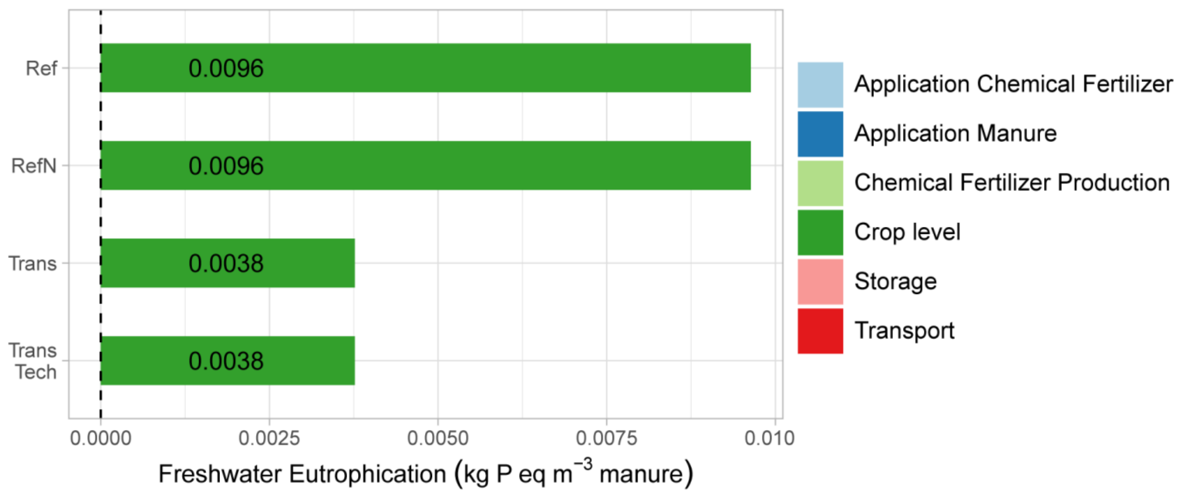

Figure 6.3 Freshwater Eutrophication for the assessed scenarios, divided into stages

Source: own calculation and illustration; numbers on the bars are the net-impact; Peq - phosphorus equivalents

6.3.3 Freshwater eutrophication

Freshwater eutrophication (FE) comprises only PO_4 losses on the crop level. PO_4 losses, as well as NO_3^- leaching losses, are summarized at the stage “crop level”. FE is low in all scenarios (0.004-0.010 kg Peq) as we assume no change in the P status of the soil and no differences regarding soil erosion in the scenarios (Figure 6.3). In the transport scenarios (Trans, TransTech), FE is 60.92% lower compared to the scenarios without transport (Ref, RefN) as shown in Table 6.5. This is caused by the higher total P application in the scenarios without transport, as the manure P exceeds plant need and does not replace chemical P fertilizer as in the transport scenarios (Section 6.2.3).

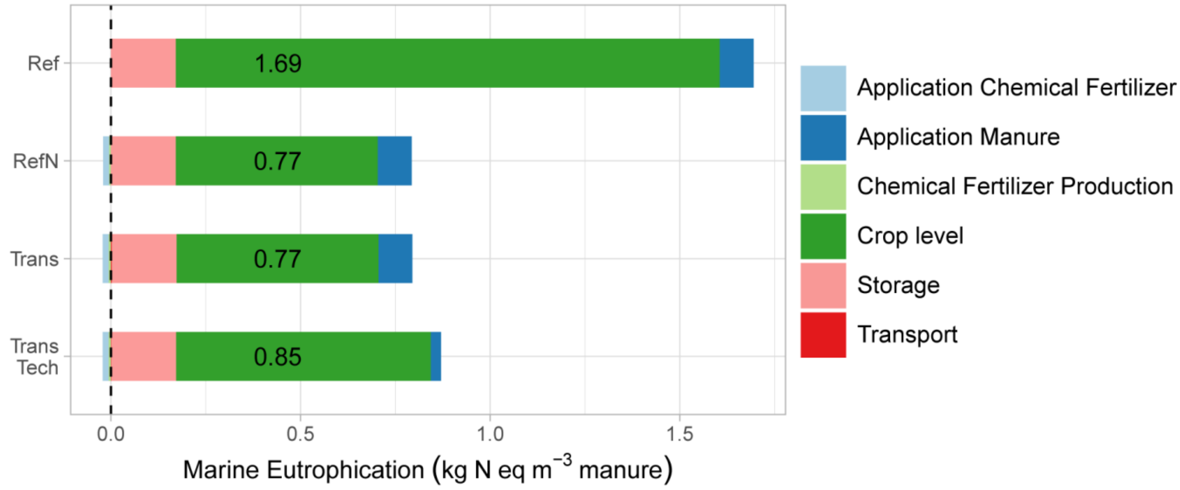

Figure 6.4 Marine Eutrophication for the assessed scenarios, divided into stages

Source: own calculation and illustration; numbers on the bars are the net-impact; Neq - nitrogen equivalents

6.3.4 Marine eutrophication

In all scenarios, marine eutrophication (ME) is dominated by NO_3^- leaching at crop level (Figure 6.4). ME is highest in Ref (1.69 kg Neq m^{-3}) due to the fact that manure N does not replace any chemical N. Thereby, the total amount of N available to leaching is higher than in all other scenarios. In Trans, ME is 54.37% lower than in Ref due to the replacement of chemical N fertilizer at the importing farm and, thereby, the reduced total N input (Table 6.5). This comparison represents manure transport under the FO 2007 and is in line with the intention of the Nitrates Directive to lower NO_3^- emissions from agriculture. ME from NO_3^- leaching is equal in RefN and Trans as manure N is replacing chemical N fertilizer in all scenarios with the same MFE, representing farmers following the fertilizer recommendations of the FO (Section 6.2.3). However, ME is higher in TransTech compared to RefN as the use of injection leads to less NH_3 losses and more N arriving in the soil. The use of standard MFE of the FO does not reflect this additional available N by adapting the chemical fertilizer use and it therefore leads to a slight increase of NO_3^- leaching.

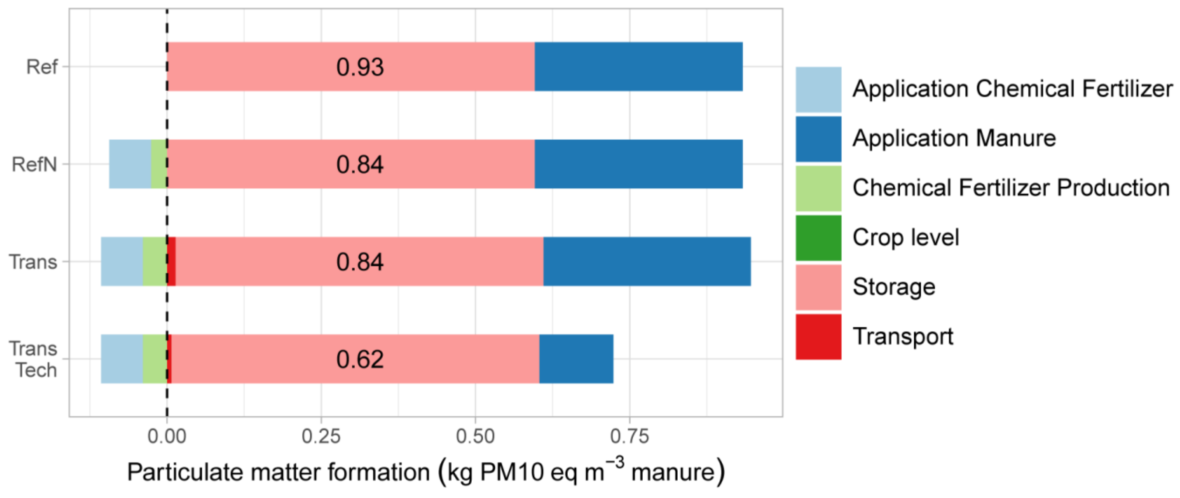

Figure 6.5 Particulate matter formation for the assessed scenarios, divided into stages

Source: own calculation and illustration; numbers on the bars are the net-impact; PM10eq - particulate equivalents

6.3.5 Particulate matter formation

In line with TA, particulate matter formation (PMF) is dominated by NH_3 emissions from manure storage and application, other emission sources contribute only slightly (Figure 6.5). Lorry transport represents a minor share of the PMF, for instance 1.2% of total PM10eq m^{-3} in Trans. The contribution of diesel combustion for on-farm transport and machinery for manure and chemical fertilizer application is even smaller, for instance 0.12% of total kg PM10eq m^{-3} in Trans.

Compared to Ref, Trans lowers PMF per m^3 by 10.05% due to the reduction of chemical fertilizer application and production which outweighs transport emissions (Table 6.5). However, compared to RefN, Trans shows only slight reductions of 0.03% caused by the replacement of chemical N fertilizer by manure N in RefN and, therefore, net savings of chemical N fertilizer emerge when comparing RefN and Trans. However, the use of injection for manure application in TransTech causes PMF to be 26.57% lower than in RefN. In line with TA, this illustrates the potential of manure application techniques with low NH_3 emissions to easily compensate PMF from lorry transport.

6.3.6 Fossil fuel and P depletion

FFD is dominated by the diesel use for transport and the energy needed to produce chemical fertilizer. In contrast to other environmental impacts, diesel for on-farm manure transport and application machinery contributes relevant shares to FFD (Figure 6.6).

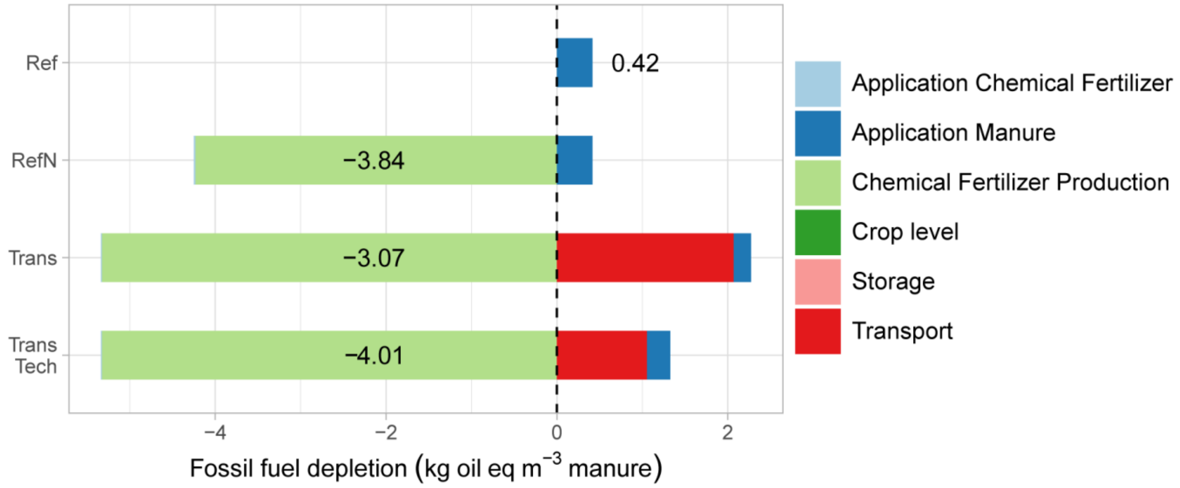

Figure 6.6 Fossil fuel depletion for the assessed scenarios, divided into stages.

Source: own calculation and illustration; numbers on the bars are the net-impact; eq - equivalents

FFD is negative (-3.07 kg oil eq m^{-3}) in Trans whereas it is positive in Ref (0.42 kg oil eqm^{-3}) as shown in Table 6.5. In Trans, the reduction in FFD from savings in chemical fertilizer (-5.33 kg oil eq m^{-3}) is larger than the FFD from transport (2.07 kg oil eq m^{-3}) leading to net savings. There is no on-farm transport of manure in Trans as manure is directly delivered to the field. This reduces FFD from on-farm machinery from 0.42 kg oil eq m^{-3} in Ref to 0.20 kg oil eq m^{-3} in Trans which does, however, not outweigh the higher emissions from lorry transport. The comparison between Ref and Trans shows the reducing effect manure transport has on FFD, induced by the FO 2007. However, when manure transport is triggered by the strict thresholds regarding P application of the FO 2017, FFD increases by 0.77 kg oil eq m^{-3} due to the need to compensate exported manure N with chemical N fertilizer. This is represented by the comparison of FFD in RefN (-3.84 kg oil eq m^{-3}) and Trans (-3.07 kg oil eq m^{-3}). However, the use of improved technology (TransTech) can compensate this increase as FFD from transport are almost halved. In Trans and TransTech, P depletion is reduced by 2.93 kg P_2O_5 in fertilizer compared to Ref and RefN, caused by the replacement of chemical P fertilizer based on fossil sources with manure P (not shown in figures). These results illustrate a possible trade-off between the reduction of P and FFD.

6.3.7 Sensitivity analysis

The variation of five parameters leads to a variation of the results above 20%, results are presented for relevant impact categories and scenarios in Table 6.6. The increase and decrease of the factor for FFD from the production of chemical fertilizer by 25% leads to a variation of FFD per m^3 manure up to 35%. Lower NH_3 emissions from storage only lead to a reduction above 25% in the scenario TransTech which is caused by the lower total NH_3 emissions due to the use of injection for manure application. GWP is in all scenarios highly sensitive to a variation of the N_2O EF for manure and chemical fertilizer application. Due to the high GWP of N_2O, small changes have a large effect in this impact category. Furthermore, assumptions with regard to the transport distance between the importing and exporting farm strongly influence results on FFD. In Trans, a transport distance of 30 instead of 75 km increases the saved FFD by 41%. A transport distance of 250 km has the largest relative impact and lowers the saved FFD by 158% in Trans and by 61% in TransTech. In Trans, there is even a rise of FFD by 1.76 kg oil eq instead of a reduction of 3.07 kg oil eq meaning that the saved FFD from chemical fertilizer production does not outweigh the diesel need from transport anymore.

For the conclusion of the study, it is essential whether the ranking of scenarios varies due to parameter variation in the sensitivity analysis. The ranking of the scenarios changes for GWP due to a higher EF for indirect N_2O following leaching. Here, the scenario TransTech has higher GWP than RefN. This is caused by the higher NO_3^- leaching as the higher plant available N due to the use of injection is not reflected by the fixed MFE of the FO. However, the most severe changes in the ranking of the scenarios are observed for GWP and FFD due to different assumptions regarding transport distances between exporting and importing farms. When manure is only transported 30 instead of 75 km, there is no increase of GWP or FFD caused by manure transport under the FO 2017. In contrast, the increase of the transport distance from 75 to 250 km strongly impacts the ranking of scenarios. In this case, Trans has higher FFD compared to Ref, although still having a lower impact on GWP (transport under FO 2007). The increasing effect of transport under the FO 2017 on GWP and FFD is not compensated by the use of lorries combining the transport of grain and manure if the transport distance is 250 km. This is reflected by the GWP and FFD being higher in TransTech than in RefN.

Table 6.6 Results of sensitivity analysis

		GWP [CO_2eq]	TA [SO_2eq]	PMF [PM10eq]	FFD [oil eq]
Baseline	Ref	153.80 kg	6.78 kg	0.93 kg	0.42 kg
	RefN	91.17 kg	6.32 kg	0.84 kg	-3.84 kg
	Trans	93.56 kg	6.30 kg	0.84 kg	-3.07 kg
	TransTech	89.98 kg	4.63 kg	0.62 kg	-4.01 kg
Lower factors for FFD from chemical fertilizer production					
	RefN				-27.59%
	Trans				-34.52%
	TransTech				-26.38%
Higher factors for FFD from chemical fertilizer production					
	RefN				27.59%
	Trans				34.52%
	TransTech				26.38%
Lower emission factor for NH_3 emission from manure storage					
	TransTech		-27.39%	-26.80%	
Lower emission factor for N_2O following application					
	Ref	-22.47%			
	RefN	-23.81%			
	Trans	-23.20%			
	TransTech	-24.12%			
Higher emission factor for N_2O following application					
	Ref	64.19%			
	RefN	68.02%			
	Trans	66.29%			
	TransTech	68.92%			
Higher emission factors for indirect N_2O following leaching					
	Ref	33.23%			
	RefN	20.82%			
	Trans	20.29%			
	TransTech	26.59%			
Lower transport distance					
	Trans				40.52%
Higher transport distance					
	Trans				-157.57%
	TransTech				-61.36%

Source: own calculation and illustration; only parameter and related impact categories which changed more than 20 % compared to the baseline, values indicate the relative change compared to the baseline; N_2O - nitrous oxide; NH_3 - ammonia; Ref - reference scenario without transport; RefN - reference scenario without transport and the replacement of chemical N fertilizer; Trans - transport scenario; TransTech - transport scenario with improved technology; GWP - global warming potential; TA - terrestrial acidification; PMF - particulate matter formation; FFD - fossil fuel depletion

6.4 Discussion

Our results show that manure transport reduces several environmental impacts compared to a situation without transport. However, we find that this reducing effect diminishes when the manure exporting farm has to replace exported manure N with chemical fertilizer.

6.4.1 Comparison to previous research

Previous studies use transport of unprocessed manure as a reference for comparison with scenarios which combine transport and manure processing (Lopez-Ridaura *et al.* 2009, p. 1298; De Vries *et al.* 2013, p. 1590) or apply a scenario without transport as reference (Hoeve *et al.* 2014, p. 61). Hanserud *et al.* (2017, p. 4) and Hoeve *et al.* (2016, pp. 712, 715) compare a scenario without transport to a scenario with unprocessed manure transport as we do in this study. Relating our results to these studies allows to compare the contribution of each stage of the manure life cycle and to detect differences due to the inclusion of the legislation triggering manure transport.

We identified CH_4 losses from storage as the main source for GWP per m^3 manure excreted which is in line with previous research (Willeghems *et al.* 2016, p. 16; Brockmann *et al.* 2014, pp. 275f.). Furthermore, manure application has the second largest impact on GWP due to N_2O emissions from manure application as other studies have found (Hoeve *et al.* 2014, p. 65; De Vries *et al.* 2013, p. 1592). Our results suggest that saved GWP from chemical fertilizer production are larger than emissions from lorry transport which confirms findings from previous studies (Lopez-Ridaura *et al.* 2009, p. 1302; Prapaspongsa *et al.* 2010, p.1419). Comparing the Ref and the Trans scenario, saved fossil resources from chemical fertilizer production exceed resource need for lorry transport which confirms results from Lopez-Ridaura *et al.* (2009, p. 1302), De Vries *et al.* (2012, p. 179), and Brockmann *et al.* (2014, p. 276) but contradicts with the findings of Hanserud *et al.* (2017, p. 11). The latter is caused by the assumptions of very high transport distances in their study. However, there is a rise of FFD when the exporting farm has to increase the chemical fertilizer use due to exports induced by the FO 2017. Hoeve *et al.* (2016, pp. 714f.) found in a case study for Denmark a reducing effect of manure transport induced by P regulations on FFD and GWP. Differences to this study are mainly caused by calculated higher savings from replaced chemical fertilizer and the varying definition of the functional unit.

The current study finds NO_3^- emissions on crop level as the most relevant emission source for ME and a relevant source of indirect N_2O emissions which is confirmed by other studies (e.g. De Vries *et al.* 2012, pp. 178ff.). However, we detect large differences with regard to the extent of ME compared to other studies (Hanserud *et al.* 2017, p. 11; De Vries *et al.* 2013, p. 1592). For example, we find a more than 300% higher ME in Ref of this study in comparison to the results of Hoeve *et al.* (2014, p. 66). This is caused by the fact that manure does not replace any chemical N in Ref and, therefore, the NO_3^- losses are higher. However, it has large impacts on the comparison between Ref and Trans, representing the fertilizer transport under the FO 2007. This shows the importance to include, in contrast to previous studies, the over application of manure N in a situation without transport and its reduction due to transport induced by legislations. This is also in line with the goal of the Nitrates Directive which causes transport in most cases and aims at reducing NO_3^- emissions on the manure exporting farm.

6.4.2 Emission calculation and sensitivity of results

To quantify emissions from different sources, we relied on EF and calculation schemes from the literature, including the specifications for the German reporting under international reduction commitments like the Kyoto Protocol or the Directive on the Reduction of National Emissions of Certain Atmospheric Pollutants. For CH_4 and NH_3 storage emissions, NO_3^- leaching, and P losses, we used more detailed calculation schemes which take location parameters, as for instance soil or climate, into account. However, as location parameters are assumed to be identical in all scenarios, they do not influence the ranking of the scenarios. In general, different emissions are highly dependent on specific climate conditions or management and are related to high uncertainty. Previous studies discussed shortcomings of standard emission accounting and illustrated possibilities for improvement (Lopez-Ridaura *et al.* 2009, pp. 1302f.; Hoeve *et al.* 2014, p. 69).

To address the high uncertainty, we did a sensitivity analysis on numerous EF, calculation schemes, and crucial assumptions, showing that the order of the scenarios does not change except for EF for N_2O following leaching and changes in the transport distance. The latter strongly impacts on GWP and FFD and changes the ranking of scenarios in our study. The key question in this context is if transport distance is higher under the FO 2017 compared to the FO 2007. It can be argued that under the FO 2017 transport distance will increase because more manure has to be transported and, hence, longer distances occur. As detailed data on current and projected transport distances are not accessible or missing, we decided to keep transport distance in both scenarios constant and cover the issue in our sensitivity analysis. With no information on maximal transport distance, we made an extreme assumption with 250 km to also assess potential long distance transports.

There are several environmental impacts that are usually not considered in LCA but related to manure transport, as for instance odor, noise from on-farm and long distance transport, or sanitary issues. Research is needed to improve data availability for including these impacts in future LCA on manure transport. Especially, as they limit the willingness of farmers to import manure, as Case *et al.* (2017, p. 92) show for odor emissions from organic fertilizers. Hence, research on the aforementioned impact categories and their reduction is of special concern when manure transport should be promoted as a measure to reduce environmental impacts of regionally concentrated livestock production.

6.4.3 Increase of chemical N use

As we show in Section 6.2.3, the strict thresholds regarding P in the FO 2017 can increase the chemical N fertilizer use of the manure exporting farm when farmers follow the fertilizing planning required by the FO. By comparing the scenarios RefN and Trans, we assess how this impacts emissions and resource need through manure transports. However, there are agronomic measures to reduce the need of exporting manure to meet regulations regarding P. Lowering the amount of P_2O_5 in manure by adapting feeding practices (Schröder *et al.* 2011, pp. 827f.) or replacing chemical starter fertilizer with manure in maize (Federolf *et al.* 2016) can lower the P input to the system. In the same way, higher N delivery from soil, as we assumed in our study, further diminishes the chemical N fertilizer need. Finally, manure processing techniques, which accumulate P_2O_5 in a solid phase (Hoeve *et al.* 2014, pp. 62ff.), allow exporting surplus P_2O_5 and keeping needed N on the farm. Our results illustrate exemplary how regulations regarding P_2O_5 can impact the N management. This is of recent interest because, alongside with Germany, further countries have introduced stricter policies with regard to P_2O_5 (e.g. Mann & Grant 2015, p. 11). Though, the extent to which farmers need to replace exported manure N with chemical N fertilizer depends highly on P and N status of soils, farmers' current management, and choice of adaption strategies. A key question is to what degree farmers can increase MFE above values set in the FO. The lack of accessible and detailed farm data regarding manure and, especially, chemical fertilizer use, in Germany, prevents us from assessing this question.

6.4.4 Policy implications

Manure transport is caused by policies to reduce the nutrient load to water bodies, as for example by the Nitrates Directive. The results of this study show that also other emissions and resource depletion decrease due to manure transport and that there is no trade-off between different environmental impacts. Hence, policies should promote manure transport as a measure to, especially in the short-term, comply with environmental regulations. This can be done, for instance, by promoting the building of manure storage facilities in manure importing regions.

However, the beneficial impact of manure transports diminishes, leading even to a rise of FFD and GWP, when manure exporting farms need to increase the use of chemical N fertilizer as we show by comparing scenarios RefN and Trans. It leads to a tradeoff between reducing P depletion and an increase of FFD and GWP. Policymakers should be aware of this possible trade-off when designing measures regarding P application. In Germany, different institutions demand that the P surplus of farms on highly P-enriched soils should not be 0, as prescribed by the FO 2017, but negative (e.g. SRU 2014, pp. 15f.). This measure would potentially increase the need to compensate exported manure N with chemical N fertilizer. It is hence advisable that it should be accompanied by measures to prevent this increase by, for example, promoting P reduced feeding strategies or subsidizing technologies which replace chemical starter fertilizer by manure in maize.

Furthermore, we assume the same vulnerability to emissions in all scenarios, meaning the relation between emissions and environmental impact is equal, which allows drawing more general conclusions from LCA results. Manure transport, although leading to a net saving of emissions, is linked to an increase in emissions on the manure importing farm. This is, for instance, the case for NO_3^- leaching or NH_3 emission due to higher application losses and lower nutrient use efficiency of manure compared to replaced chemical N fertilizer. When manure is transported to vulnerable areas, the environmental impact can increase although a net saving of emissions is present as we show in our study. Therefore, policy needs to limit or prevent the transport to certain areas, as for instance regions with low groundwater recharge or areas neighboring natural or semi-natural habitats. This can be done by linking nutrient application thresholds to local vulnerability or existing pollution pressure as introduced for areas with high NO_3^- groundwater and P surface water pollution in the FO 2017.

6.4.5 Strength and weaknesses of the LCA approach

The strength of LCA is the comprehensive judgement of the environmental impact of manure transport, taking numerous impact categories into account. Furthermore, LCA results detect possible trade-offs and combined benefits between different emissions and resource depletion linked to manure transport. Nevertheless, the weighting of opposed environmental impacts is challenging and related to high uncertainty and, from a policy point of view, makes conclusive judgements from LCA results difficult. As in our study the majority of impacts decreases, this limitation is of minor concern.

Finally, manure transport is one measure of farmers to comply with legal requirements. It is a dominant adaptation measure as results from countries suggest which already have a strict implementation of the Nitrates Directive in place (e.g. PBL 2017, pp. 60ff.) and as the transport under past legislation in Germany illustrates (Section 6.1). However, socio-economic drivers determine how farmers react to changing legal conditions. Thereby, the use of manure transport to comply with environmental legislation is limited by its high costs. Farmers may also adopt agronomic measures, increase land endowment, or exit the market instead of transporting manure. Furthermore, it is likely that stricter environmental regulations have an impact on the extent and location of EU livestock production, especially in the long term. Hence, our results illustrate the environmental impact of a single adaption measure but should not be understood as a general environmental impact assessment of the Nitrates Directive or its implementation in Germany which needs other approaches than LCA.

6.5 Conclusion

The transport of manure is a key measure of livestock farmers to comply with environmental legislation like the Nitrates Directive. Our results indicate that transport reduces all assessed environmental impacts compared to a situation without transport. Comparing the management of manure with and without transport, major declines are realized for GWP (39%), ME (54%), FE (61%) and PMF (10%). Furthermore, FFD declines by 0.77 kg oil eq and 2.93 kg chemical P_2O_5 fertilizer is saved per m^3 of manure. Reductions are mainly driven by the replacement of chemical fertilizer with the manure on the importing farm and an increase in nutrient use efficiency on the exporting farm, understood as lower nutrient input in relation to a constant output. However, our analysis shows that this reduction diminishes when manure export is caused by stricter measures regarding P_2O_5 application which can lead to an increase of chemical N use on the manure exporting farm. In this case, FFD rises by 20% and GWP by 3%. We conclude from this study that it is crucial to explicitly comprise the regulations triggering manure transport when assessing its environmental impact by LCA. Furthermore, policymakers should be aware of possible trade-offs between strict measures to lower P depletion and FE and the possible increases in FFD and GWP. They can be tackled by promoting measures like manure processing or low P excretion feeding as well as innovative technology like the combined transport of manure and cereals. The latter compensates, as our analysis shows, the increase in FFD and GWP by avoiding empty trips. To further assess the relation between legislations and the environmental impact of manure transport, future research should assess the amount of transported manure as well as the change of transport distances in relation to the implementation of stricter environmental legislation.

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Chapter 7

Conclusion

The revision of the Fertilization Ordinance (FO) in 2017 changes the regulation on the fertilizing management in German agriculture. The overall research aim of this thesis is the analysis of the environmental and economic impact of the revision at farm-level, focusing on Northwest Germany. The following chapter combines the contribution and policy implications of the previous chapters in this thesis. Furthermore, the applied methodology is critically reflected and a research outlook is given. The FO is going to be again revised in 2020, as the EU Commission considers the current legislation as insufficient to fulfill the EU Nitrates Directive. The proposed changes are already publicly discussed and briefly summarized in the following chapter. Furthermore, they are evaluated based on the results of this thesis and taken up in the research outlook as well as in the policy implications.

7.1 Major contributions of the thesis

This thesis finds that the economic impact, understood as the induced costs to comply with the regulation, as well as the environmental impact of the FO 2017 are highly heterogeneous and strongly depend on farm characteristics. The analysis of the on-farm compliance costs for specialized livestock farms in North Rhine-Westphalia (NRW) reveals that 47% of the pig fattening and 38% of the dairy farms do not face any compliance costs. They range from 0 to 2.66 Euro (€) pig^{-1} and 0 to 0.83 cent (ct) (kg milk)$^{-1}$ for pig fattening and dairy farms, respectively. Farms with low compliance costs mainly face costs due to the compulsory low-emission manure application techniques. Pig fattening farms with higher stocking density face high costs to comply with the stricter nutrient application thresholds under the FO 2017. As the phosphate (P_2O_5) surplus restriction is most binding for manure application, the phosphorus (P) soil status strongly determines the compliance costs. Dairy farms are found to face no compliance costs to meet stricter nutrient application threshold as manure application is limited by the manure N application threshold, which stays unchanged under the FO 2017. Their main cost driver is the absence of low-emission manure application techniques and a high share of grassland. The latter makes manure application costlier, since low-emission techniques are slightly more expensive on grass than on arable land, and farms can apply less manure on bare land, followed by immediate incorporation into the soil.

For selected pig fattening farm types in NRW, this thesis also contributes to an estimation of the changed environmental impacts. Intensive pig fattening farm types with a high stocking density reduce their nitrate (NO_3^-) leaching from 50 to 38 kg NO_3^--Nitrogen (N) ha^{-1} and ammonia (NH_3) volatilization from 82 to 73 NH_3-N ha^{-1}, to name the most important changes.

Reductions are mainly realized by the export of excess manure due to the stricter P_2O_5 surplus limit, the introduction of low-emission manure application techniques, and the move from manure application from autumn to spring. However, such pig farms only account for 3.50% of the pig stock and for 0.47% of the farms in NRW. Farm types with lower stocking density, which do not need to adapt to stricter nutrient application thresholds, realize only little emission reduction, mainly due to the compulsory use of low-emission manure application techniques. They represent 17.62% of the pig stock and 2.22% of the farms in NRW. In line with the compliance costs, no or only slight emission reduction is found for a large share of the assessed pig fattening farms. This illustrates that the contribution to environmental targets might be small and thus makes the nationwide attainment of environmental targets related to the FO questionable.

Furthermore, this thesis contributes to a comprehensive assessment of manure transport induced by the FO. From an economic point of view, the transport of excess manure is identified as a major and cost-efficient compliance strategy of livestock farms to fulfill stricter nutrient application thresholds. However, the statistical meta-model reveals that the price of manure transport have a significant impact on compliance costs and, thus also on its selection as a compliance strategy in favor of reducing stocking density. Manure import is highly profitable for manure accepting arable farms. The assessed arable farm types are able to lower costs from 98 and 108 € ha^{-1} when importing 15 and 20 m^3 ha^{-1}, respectively. The saved variable costs for chemical fertilizer overcompensate the higher costs for manure application by far. Furthermore, none of the importing arable farm types reaches the thresholds of the FO 2017 when using manure.

From an environmental point of view, however, manure transport is found to cause pollution swapping. Generally, pollution can swap from one region to another as well as from one environmental impact to another (Oenema & Velthof 2007, p. 31). In this thesis, the environmental impact of manure import on arable farm types in NRW is assessed. They increase NO_3^- leaching as well as NH_3 volatilization. For the arable farm type importing 15 m^3 ha^{-1}, for example, NO_3^- leaching rises from 40 to 46 kg NO_3^--N ha^{-1} and NH_3 volatilization from 1 to 9 kg NH_3-N ha^{-1}. The leaching rate is provided by the crop modelling framework SIMPLACE, representing soil and climate in NRW. The use of manure implies a higher total N input as manure N and chemical N are not one-to-one replaced. Hence, the total amount of N applied increases, and the danger of leaching loss rises. NH_3 volatilization enlarges as manure application is linked to higher gaseous losses than the application of the replaced chemical fertilizer. Consequently, the negative environmental impacts on the manure importing farm increase.

Related to 1 m^3 of manure and compared to a situation with the application of excess manure above plant need, manure transport lowers all assessed environmental impacts. Increases on the importing farm are compensated by decreases on the exporting farm. Major reductions are realized for the global warming potential, freshwater and marine eutrophication, as well as fossil fuel and P depletion. The additional GHG emissions from the lorry transport are overcompensated by the saved emissions from chemical fertilizer production and reduced nitrous oxide emissions. Under the FO 2017, however, manure export from pig fattening farms is partly induced by stricter P_2O_5 surplus limitations. In this case, N leaves the farm together with the exported P_2O_5 and is replaced by chemical N fertilizer to sustain plant need and the positive environmental effects of manure transport diminish. Larger reductions are only found for freshwater eutrophication and P depletion. global warming potential and fossil fuel depletion even rise compared to a situation without manure transport due to the lower amount of saved chemical fertilizer. Hence, pollution swaps between different environmental impacts. These findings illustrate the need to judge the environmental impact of manure transport in relation to the regulations that trigger transport. The use of low-emission manure application techniques and lorries, which combine manure and grain transport and, thereby, reduce empty drives, lower NH_3 as well as GHG emissions and save fossil fuels. Such technical measures can counterbalance the negative environmental impact of manure transport induced by the FO 2017 and realize environmental benefits in all assessed impact categories.

The FO 2017 is a multi-pollutant policy and consists of numerous, partly interlinked measures. They are simultaneously analyzed in this thesis to understand their combined impact and interaction, which is especially valuable for the different nutrient application thresholds. For pig fattening farms, the P_2O_5 surplus limitation is most binding for manure application whereas the organic N application threshold limits the manure application of dairy farms. When fulfilling the most binding threshold, the other ones are met likewise. Arable farms do not meet any nutrient application threshold under the FO 2007 and 2017, except for compulsory fertilizing planning. It is found to be only restrictive for a farm-type that operates at a part of the N yield response function where the yield return from additional N is very small and yield decreases are linked to negligible costs. However, the statistical meta-model illustrates that the results are depending on assumptions on the fertilizing management, such as the mineral fertilizer equivalents of manure N and the minimum chemical fertilizer need of crops.

Regarding the methodological contribution, the main achievements of this thesis are the implementation of the FO measures in the FarmDyn and the coupling of the farm model to the crop modelling framework SIMPLACE. The latter provides NO_3^- leaching and yields for crop rotations under different management regimes and at different locations in NRW. The data allows a detailed and site-specific representation of bio-physical attributes of the cropping activities in FarmDyn and, hence, a sound analysis of the FO. This thesis provides the conceptual as well as technical integration of the two models, which can be transferred to similar modelling exercises. The use of farm models, however, requires the decision on which farms to assess. In the course of the application of the coupled models, a unique farm-typology for NRW is developed based on official single-farm statistics. The typology gives insights into the relevance of different farm types in the population and, thereby, enables the selection of the farms for the assessment. Furthermore, it provides important data for the model parametrization and initialization from a current and comprehensible data source. The complete typology for selected farm types, covering around 77% of the farm population of NRW, is provided as well as a detailed description of the methodology to easily update and extend the typology with upcoming official statistical surveys. Besides modelling selected farm types, the compliance costs with the FO are assessed for a whole farm population. However, single farm data from official German statistics cannot be directly accessed by scientists due to data protection requirements. Therefore, a sampling approach is used to create a representative farm sample based on the observed distribution and correlation of relevant farm characteristics, which allows combining different data sources. This thesis thereby contributes a blueprint for future modelling of farm populations when facing restricted data access and diverse data sources.

7.2 Revision of the FO in 2020

Although just having been revised in 2017, a new FO revision is discussed in spring 2019 and planned for 2020. The EU Commission sees the FO 2017 as insufficient to fulfill the Nitrates Directive. Therefore, the German government has to provide an improved regulation to avoid infringement proceedings, which may lead to high penalty payments. The German government submitted proposals to the EU Commission at the end of January 2019 (Agra-Europe 2019b, pp. 35f.). Official documents are not yet available to the public and, therefore, the following measures stem from media reports and are uncertain and preliminary.

Already under the FO 2017, federal states have to take at least three additional measures in regions that exceed target values of the NO_3^- concentration in water bodies. However, the available measures are mostly unambitious. They have been excluded from the thesis as the decision in NRW on the selection of measures was just taken in January 2019 (MULNV 2019). The upcoming FO revision though focuses on the reduction of NO_3^- emissions in such regions and proposes the following additional and considerably tighter measures (Agra-Europe 2019b, pp. 35f.):

- Compulsory cultivation of catch crops before summer crops
- Ban of fertilizer application in autumn for winter barley and winter rapeseed
- Lowering of the N target value of the fertilizing planning by 20% compared to regions that do not exceed NO_3^- targets

- Calculation of the manure application threshold of 170 kg N ha^{-1} at plot instead of farm-level
- Reduction of the manure application threshold from 170 to 130 kg N ha^{-1}
- Extension of possibilities for federal states to implement additional measures

The first four named measures are not optional measures for federal states but compulsory in regions exceeding NO_3^- target concentrations in water bodies (top agrar 2019). In addition, the following measure is discussed as a nationwide adaption, independent of the NO_3^- concentration in water bodies (Agra-Europe 2019b, p. 35):

- Replacement of the nutrient balance and surplus limitations by plot specific recording of the applied fertilizer to better capture the compliance with the fertilizer need derived in the fertilizing planning

The proposed measures are not part of the thesis at hand, but its findings are valuable for a first evaluation. For the intensive pig fattening farm type in Chapter 4, the move of manure application from autumn to spring in winter barley is found to cause a large reduction in NO_3^- leaching. Generally, fertilizer application in autumn is linked to higher leaching losses than in spring (Cameron *et al.* 2013, p. 151). Hence, restricting application in autumn as well as the compulsory growing of catch crops, which increases the uptake of excess nutrients before winter from the previous crop, is a sound measure to further reduce NO_3^- loss. Livestock farms having less than 3 livestock units (LU) ha^{-1} need to hold a manure storage capacity for 6 months only. This is most likely insufficient to gap the longer period when manure application is forbidden, as results on the medium intensive pig fattening farm in Chapter 4 show.

Lowering the target value of the fertilizing planning by 20% requires all farm types assessed in Chapter 4 to adapt their farm management. In the modelling exercise, farms would most likely comply with the lower target value by reducing the fertilizing intensity and accepting yield decreases. The arable farm type, which has to reduce fertilizer use to fulfill the fertilizing planning under the FO 2017, considerably lowers NO_3^- leaching at little yield losses and costs. However, the actual reduction of NO_3^- leaching and related costs are difficult to predict without rerunning the model, as it depends on the crop, soil and climate specific yield response of N fertilization in relation to the target value of the fertilizing planning.

The reduction of the manure N application threshold from 170 to 130 kg N ha^{-1} will cause a leaching reduction as well as high costs for some farm types. Chapter 4 shows that higher manure N use tends to result in increased NO_3^- leaching, as the total amount of applied N is higher. Therefore, arable farms importing manure face increased leaching. Conversely, reducing manure N will lower total N application and leaching. The analysis in Chapter 5 reveals that the manure N application threshold is most binding for dairy farms. A further decrease will cause costs due to the manure reduction on-farm by export or reduced stocking density. Furthermore, chemical fertilizer use increases as intensive grassland has an N need far above 130 kg N ha^{-1} (BMEL 2017b, p. 28). On pig fattening farms, the P_2O_5 surplus restriction is most binding for manure application. Hence, farms are not able to fully utilize the manure N application threshold and a further reduction has no or small effects. However, which nutrient application threshold becomes first binding for manure application highly depends on farm characteristics such as P soil status and the present fertilizing management.

Whereas the measures described above are only planned for areas exceeding target concentrations in water bodies, the nutrient balance is supposed to be replaced nationwide by a plot specific recording of fertilizing activities to better control compliance with the fertilizing planning. However, the little available information on this measure makes a first judgment difficult. The fertilizing planning of the FO 2017 already contains a total nutrient application limit depending on the predefined crop need and nutrient sources such as N mineralization from the soil pool in spring. However, farmers conduct this planning before the nutrient application whereas the recording is foreseen to be done when the actual application takes place. In the modelling setup of this thesis, the additional recording of the actual applied fertilizer does not cause changes. Crop activities represent average years without yield variation, full compliance is assumed and, hence, the defined crop need from the fertilizing planning is met. The recording of the applied fertilizer is meant to improve the enforcement of the fertilizing planning and has to be considered in the evaluation. The advantage of better enforceability of measures is thus not covered by this thesis.

As a complementary measure, the German government plans a program to support the transport of excess manure from livestock intensive regions to arable farms and the building of manure storage vessels (Agra-Europe 2019a, p. 14). The importance of the export of excess manure as a compliance strategy for livestock farmers to fulfill stricter nutrient application thresholds is confirmed by the results of Chapter 4 and 5, but also the danger of pollution swapping is shown.

7.3 Methodological discussion and research outlook

Farm models as applied in Chapter 4 and 5 are well suited to assess agri-environmental policies. They allow by definition capturing economic and bio-physical attributes of current and future farming activities as well as related externalities (Janssen *et al.* 2010, p. 863). In the context of assessing the FO revision, this enables to implement measures and compliance strategies in detail and determine their economic and environmental impact. Modelling at the farm-scale allows capturing farm heterogeneity (Blanco 2016, p. 2) and, thereby, facilitates findings on the diverse impacts of the FO depending on farm characteristics as one of the major contributions of this thesis. As supply side models, however, farm models are characterized by price exogeneity, which is a major shortcoming for their use in policy assessments. Excluding market feedback disregards possible impacts of the FO on input and output prices, which influence the on-farm compliance costs and potentially even the emission changes found in this thesis. For instance, prices for specialized feeds to realize lower nutrient excretions or for low-emission manure application techniques provided by contractors may rise due to increased demand. Furthermore, the export of excess manure is identified as a core compliance strategy of farmers to fulfill stricter nutrient application thresholds. Already under the FO 2007, high amounts of manure are transported within and between regions in Northwest Germany (LWK NRW 2014, p. 118ff.; LWK Nds. 2016, p. 142ff.). The FO 2017 boosts the manure transport, making longer transport distances from livestock intensive regions to manure importing regions necessary and, hence, increase the transport costs. A sensitivity analysis using a meta-modelling approach, as in Chapter 5, can provide insights into the impact of variations in such crucial prices. The analysis though cannot predict how the prices are influenced by the FO 2017. Furthermore, the farm-level analysis does not capture manure flows in the assessed regions, which is important to detect possible regional pollution swapping.

The results of the life cycle assessment (LCA) in Chapter 6 give insights into the emission reduction induced by manure transport and in possible pollution swapping between different emissions. However, the limitations of the applied methodology make a careful interpretation of LCA results in relation to policy measures necessary. The LCA does not show the development of the total excreted or transported manure due to the FO 2017. It might be that livestock farms lower their animal stock and exit the market due to the stricter FO 2017, which is linked to a high emission reduction. The LCA assesses one major adaption strategy to the FO, but does not allow drawing conclusions on the total emission changes induced by the policy. However, the analysis with FarmDyn shows that a reduced animal stock is not a prominent compliance strategy. The farm model though represents a short term view as investments into stables are assumed to be sunk. Research on the future investment behavior of farms in Northwest Germany, under general water protection policies but not the FO 2017, does also not find decreasing impacts on animal stocks (Budde 2013, pp. 124ff.).

The use of other modelling approaches partly overcomes the described shortcomings of the farm-level and LCA approach. The research found in Chapter 2, 3, 4 and 5 is part of an interdisciplinary research project, which addresses the economic and environmental impacts of the FO revision in NRW and focuses on the coupling of three different models across scales. Besides the crop modelling framework SIMPLACE and the farm model FarmDyn, the agent-based model ABMSim is applied (Britz 2013). ABMSim is connected downstream in the modelling chain and coupled to FarmDyn. The connection between the two models is realized with a meta-modelling approach which functions as follows: FarmDyn is run for numerous farms derived from sampling over relevant farm characteristics. Sequentially, dual profit functions are derived and control agents' behavior in manure and land auctions, which determine prices for manure export and land. The modelled agents interact on the nutrient market and manure flows are modelled in a spatially explicit way for the study area. In contrast to the farm-level approach, the agent-based model covers the interaction of manure exchange, depicts manure flows in response to the FO, and quantifies the amount of traded manure. Hence, it has the potential to capture possible regional pollution swapping if regions sensitive to increased manure inflow are identified. As the amount of traded manure is quantified, including emission factors from the LCA into the agent-based model allows estimating the total emission change due to manure transport induced by the FO and, thereby, overcomes limitations of the LCA approach. However, ABMSim does not include a market for inputs and outputs and cannot predict price changes induced by policies. To capture the impact of the FO 2017 on relevant prices, (partial) equilibrium models, which include market clearance for goods, need to be applied.

The analysis at farm-level, as well as the LCA perspective, contributes insights into the environmental impacts of the FO 2017, revealing the interaction of measures and possible pollution swapping. Due to the chosen scale and methodology, however, a direct link to existing environmental targets is not possible for multiple reasons. First, this requires an area-wide simulation of emissions at the catchment or regional scale which is neither provided by a farm perspective nor a LCA. Second, environmental targets for water bodies do not aim at emissions but at concentrations of N and P. The concentrations, however, are strongly affected by factors subsequent to the actual on-farm emission. The change of the N and P concentration in water bodies is influenced by site characteristics such as the rate of groundwater recharge, denitrification potential, field slope and distance to surface waters. Third, the actual emission change by the FO 2017 is difficult to predict due to the unknown compliance with the FO in the past. Empirical data hint at a lack of compliance (LWK NRW 2014, pp. 53ff.), however, detailed as well as representative data is not accessible. The FO 2017 includes numerous measures to improve the enforcement such as higher penalties, better data access for controlling organizations, and improved calculation schemes for nutrient balances. Hence, the FO 2017 may strongly contribute to reaching environmental targets by enforcing measures that have already been in place under the FO 2007. Due to the lack of data, this effect is disregarded in the thesis by assuming full compliance under the FO 2007 and 2017.

Alternative modelling setups can link policies to the attainment of environmental targets but have other shortcomings. Hydro-biogeochemical models, mostly operating at the catchment or regional scale, capture the site-specific processes between the actual on-farm emission and the concentrations in water bodies. To assess agri-environmental policies, such models need spatially explicit information on the emission change related to the land area. For NRW, the project GROWA+ NRW 2021 (2015-2019) couples the agricultural sector model RAUMIS to a hydro-biogeochemical modelling chain (MULNV n.d.). The aim is, among others, to assess the contribution of the FO 2017 to reach environmental targets in ground and surface waters (Bergmann 2016, pp. 13ff.). The detailed methodology and final results of the project are not yet published and the following statements are thefore preliminary. As an interlinkage to the bio-physical models, the bio-economic sector model provides N surplus at the commune level and adaptions to the FO are reflected in surplus changes. The sector model covers fewer measures of the FO and less compliance strategies than the modelling approach in this thesis. Furthermore, fewer environmental impacts are subject to research as the focus is solely on the aquatic environment. Due to the different scale, the results do not give any insights into the compliance costs at farm-level and cost differences between farm types. This illustrates that the modelling approaches are not competing but complementary.

In future research, the modelling chain of the crop, farm and agent-based models can be extended by hydro-biogeochemical models to relate emission reduction induced by policies such as the FO to environmental targets. For this type of model connection, ABMSim provides several advantageous characteristics. First, the spatial resolution of ABMSim is at the hectare level and, therefore, it is able to produce emissions from agricultural sources for a sharp delineation of an administrative unit or catchment area. Second, compared to other agent-based models, the use of profit functions to simulate agent's behavior in ABMSim facilitates modelling large number of farmers (Seidel & Britz 2017), which is helpful to capture the farm population in a catchment or a large region. However, profit functions make it a challenge for the model development to estimate the detailed emission changes of each agent induced by the FO.

A major methodological contribution of the thesis is the coupling of the farm model FarmDyn to the crop modelling framework SIMPLACE. It allows better capturing relations between yield, fertilizing and NO_3^- leaching and representing the soil and climate conditions in NRW. Further bio-physical variables can be provided by the link to specialized models and improve the bio-physical depiction of farming activities and related externalities in FarmDyn. Regarding the assessment of agri-environmental policies such as the FO, a better representation of animal feeding and emissions from stables, manure storage and application are relevant. Models can predict nutrient excretion based on feeding attributes and also reflect different genetics and climate (e.g. Rigolot *et al.* 2010). This could replace fixed and simplified relations between feed input and nutrient excretion, currently representing different feeding regimes in FarmDyn. Except for NO_3^- leaching, emissions are quantified by using standard EF from emission accounting schemes, which partly disregards their variation. Model results on environmental losses, which take climate conditions as well as more management options into account (e.g. Sommer *et al.* 2004), could improve the emission accounting in FarmDyn. Especially regarding N excretion and loss, however, the implementation in the linear programming approach is challenging. The use of detailed data from bio-physical models comes at the price of increased computing time, which makes the analysis of a whole farm population as in Chapter 5 impossible. Depending on the research questions, however, the input into FarmDyn can be downsized to reduce the number of variables entering the model. Future applications of FarmDyn, which are not focusing on the nutrient management, could for instance use simplified SIMPLACE data, containing fewer fertilizing scenarios, or aggregated N response functions derived by statistical methods.

Furthermore, one needs to be aware that the use of other models not only introduces their strengths but also their weaknesses. Results of the crop modelling framework SIMPLACE are linked to high uncertainty due to the lack of data for model initialization and calibration. Missing data on initial soil N and carbon (C) makes a spin-up period necessary to avoid the large impact of these variables on the results and to capture actual impacts of the management, as elaborated in Section 4.4.3. In addition, there is no data used from field trials on different amounts of manure and chemical N and further assessed management options. Only standard management is introduced for calibration, and the bio-physical relations underlying the crop model determine the impact of the management. To further improve the validity of the crop modelling results, data of field trials are needed that cover the actual assessed management options and provide measurements of the variables of interest such as yield and NO_3^- leaching. This allows calibration to actually observed variables in relation to different management options.

The compliance costs with the FO as well as the environmental impacts of the assessed farms strongly depend on the assumptions with regard to the fertilizing management. In Chapter 4, the relation of yield, fertilizing and related externalities is derived from the crop system modelling framework SIMPLACE and reflects soil and climate conditions of NRW. Whereas in Chapter 5 it is assumed that farms follow the fertilizing planning of the FO 2017 under the old and revised FO. In both cases, FarmDyn reflects an optimal fertilizer use but the cropping activities are characterized by different underlying relations between nutrient input and yield. However, empirical data show that the fertilizer use of similar farms is highly heterogeneous (Osterburg & Techen 2012, p. 195; LWK NRW 2018, p. 44). There is thus a large potential to reduce chemical fertilizer at constant yields on farms that do not use the optimal fertilizer doses. This effect, which could lead to negative compliance costs with the FO, is difficult to implement in an economic optimization model and, therefore, not captured by the used methodology. Thereby, an important impact of the FO is excluded. In future research, the observed fertilizer use or fertilizing efficiency can be introduced as farm characteristics into the farm typology and exogenously prescribed to the model. However, existing and accessible data on the fertilizing management of farms stem mainly from risk-based controls to enforce the FO, therefore, are strongly biased, and do not contain enough farm characteristics for a sound linkage to official agricultural statistics. To address this issue, improved access to single farm nutrient balances or fertilizing plans is essential.

Generally, the question arises why farmers apply more costly fertilizer than needed for plant nutrition. FarmDyn reflects standard economic behavior by assuming a totally rational and profit-maximizing farmer. However, (some) farmers may be risk-averse regarding fertilizer use and tend to apply more nutrients as needed because they are not willing to risk a nutrient deficiency and possible yield decreases. Research on the use of plant protection of farmers shows that their behavior differs strongly and that they aim for different goals (Pedersen *et al.* 2012). Better understanding of the heterogeneous behavior of farmers regarding fertilizer use and implementing it into farm models such as FarmDyn would improve the assessment of an important driver of nutrient loss.

The distribution of farm characteristics and the derived farm typology depend on official statistics, namely the Farm Structure Survey (FSS) as well as partly the Census of Agriculture. These data sources cover almost all farms in Germany and numerous farm characteristics, which are of importance for assessing agri-environmental policies. However, two major shortcomings limit the data reliability and, therefore, the outcome of this thesis. First, complex farming structures caused by splitting single farms into numerous legal units are not detectable. This especially limits the findings on the cost distribution in the pig fattening farm population. Second, some farm characteristics such as the present manure application techniques are not directly reported and need to be derived by restrictive assumptions. Data for farm typologies are frequently provided by experts (e.g. Budde 2013; Zimmer & Deblitz 2005), which facilitates access to detailed farm characteristics but is less comprehensible. Extending and validating statistical data-driven typologies by expert knowledge can combine the advantages of both approaches. In the context of the data-driven typology derived in Chapter 3, experts could add farm types consisting of numerous farming units, validate the farm characteristics based on restrictive assumptions, and add information on the fertilizing management. The distribution of farm characteristics in the farm population is difficult to obtain from experts and, therefore, improvements are dependent on changes in the information provided by official statistical surveys, as laid down in Section 7.4.

The developed modelling setup can be easily used to assess the proposed changes of the FO in 2020 as well as of the compulsory farm gate balance, which was introduced in a regulation separated from the FO (BMEL 2017a). Implementing the new and changed measures in FarmDyn and assessing their impact on the farm types presented in Chapter 4 allows judging the additional costs and emission reduction. Regarding the analysis of the cost distribution in the farm population, the measures of the FO 2020, which focus on areas exceeding NO_3^- threshold in water bodies, are challenging to capture. Information is needed if farms are located in such areas and, more precisely, the share of land of a farm affected by stricter measures. The latter is not included in official agricultural statistics, which makes restrictive assumptions necessary. Furthermore, the move from surplus restrictions to fertilizing limits is apparently motivated by better enforcement (Agra-Europe 2019b, p. 35). This effect cannot be captured by the current modelling approach that acts on the assumption of full compliance.

In a previous version and independent from the main model development, FarmDyn is used to assess the investment behavior under different water protection policies (Budde 2013). In this study, the dynamic instead of the comparative-static setting is used. Compliance strategies as well as the bio-physical representation of livestock and plant production are captured at much lower detail as in this thesis. Future research could repeat the modelling exercise on investment behavior with the current FarmDyn version and address the detailed implementation of the FO 2017 or 2020 instead of general water protection policies. However, as investment behavior is strongly influenced by factors which are exogenous to a farm model such as prices for land, manure export, and labour as well as regional restrictions by building laws, alternative modeling approaches such as agent-based models are more promising.

FarmDyn is a generic model and can be parameterized for other regions than Northwest Germany. Current model developments aim at a stronger modulation of the model structure, which facilitates replacements of region-specific parameters and constraints. For example, the measures of the FO could easily be replaced by the implementation of the Nitrates Directive in other EU Member States. Therefore, future model applications could aim at assessing other countries' agri-environmental policies on nutrient loss and at cross-country comparisons.

7.4 Policy implications

The costs to comply with the FO are found to be highly heterogeneous in the farm population and depending on farm characteristics such as stocking density or soil P status. Therefore, enforcement efforts as well as supporting measures should be targeted to the affected farms. In Chapter 5, pig fattening farms with high stocking density and P enriched soils are identified as having the highest cost burden. Therefore, their incentive for non-compliance is highest and they should be in the focus of the enforcement. Existing support programs focus on manure application techniques (e.g. MKULNV 2015) as well as the exchange of manure between farms (e.g. Nährstoffbörse NRW n.d.). In relation to the FO 2020, policymaker at the federal level plan measures to support manure transport from livestock intensive regions to arable farms (Agra-Europe 2019a, p. 14). The low-emission manure application techniques cause costs for a high share of the farm population, but the cost burden is small compared to farms which have to lower their nutrient surpluses. Hence, investment support for manure application techniques reduces the costs of a broad share of the farm population. In contrast, supporting manure exchange helps fewer farms with partly such high compliance costs that the continued farm operation may be at risk. Hence, the chosen support measures need to be reflected in relation to the political objectives.

Besides the compliance costs, the realized emission reduction due to the FO 2017 is also highly heterogeneous for specialized pig fattening and arable farms, as shown in Chapter 4. Farm types, representing a high share of the underlying farm population and animal stock, do not show any or only slight emission changes. The findings suggest that the emission reduction are likely insufficient to meet the environmental targets, especially the NO_3^- concentration in ground and surface waters, as only a share of farms has to adapt to the FO 2017. As discussed above, this thesis is not able to finally address this issue as the methodology does not allow a direct linkage to environmental targets, the created farm typology and population is related to uncertainty, and the estimation of the emission reduction due to stricter enforcement is unknown. To better address the latter in the future, data on nutrient surpluses should be collected nationwide. Under the FO 2017, this is an optional measure for federal governments and is planned to be introduced in NRW (MULNV 2019).

As stated above, the on-farm costs, as well as the emission reduction, depend on farm characteristics. The FSS and the Census of Agriculture are the only source for nationwide single farm data that cover almost all farms and are used in this dissertation. However, complex farming structures are not detectable, which limits the validity of the distribution of farm characteristics as well as the farm typology and, therefore, of the derived compliance costs. Capturing the existing farming structure is generally of importance for science based political consulting and, especially, to judge farm income and structural change. Policymakers can improve the quality of these data sources. The combination of related farming units to one farm is already optional in official agricultural statistics but only done in Lower Saxony and Schleswig-Holstein (Forstner & Zavyalova 2017, pp. 33ff.). As a first step, policymakers in other federal states, such as NRW, can use this existing possibility to increase the data quality. This allows better capturing the relation between land and livestock. However, diverse structures of farms, including activities such as renewable energy generation, would still be unidentifiable.

The thesis shows that manure transport induced by the FO 2017 causes pollution swapping between different environmental impacts as well as different regions. The swapping between environmental impacts is mainly found between lowering fossil P depletion and freshwater eutrophication compared to increasing GHG emissions and fossil fuel depletion. It is related to the FO 2017 if the manure export is caused by the strict P_2O_5 threshold and the exporting farm needs to increase its chemical N fertilizer use. Higher GHG emission levels can be reduced or prevented if farmers increase the mineral fertilizer equivalents of manure, which leads to less exported manure N and thus less chemical fertilizer to replace it. Nonetheless, the economic incentive for manure exporting farms is small as additional fertilizer costs are found to be minor compared to other compliance costs. Policymaker can stimulate this by lowering the loss factors in the fertilizing planning or the nutrient balances, which are in part very high in the FO 2017 and do not reflect the current state of knowledge. The N use efficiency of manure, however, is limited by its bio-physical characteristics. In addition, processing techniques to partly split manure N and P_2O_5 and export only the excess nutrient can lower the increase in chemical fertilizer use. Also special lorries, which reduce empty drives by transporting grain when returning from manure transports, counterbalance the pollution swapping induced by the FO 2017, as shown in Chapter 6. Financial support measures can foster the use of such techniques. Thereby, the environmental impact of processing techniques needs a careful assessment as they may cause pollution swapping as well (e.g. De Vries *et al.* 2012).

Manure transport from livestock to arable farms is promoted by policymakers to support farms in livestock intensive regions to comply with the FO (LWK Nds. 2018; Nährstoffbörse NRW n.d.). However, manure use increases NO_3^- leaching as well as NH_3 volatilization on the importing farm and, hence, causes regional pollution swapping. One can argue that this swapping is irrelevant if the net-change of emissions is negative. However, the environmental damage of NO_3^- and NH_3 emissions is depending on the location. Manure import is of special concern when taking place in environmentally sensitive areas such as regions already exceeding NO_3^- and P concentration targets in ground and surface water or being close to natural or semi-natural habitats. Policymaker can prevent negative impacts of regional pollution swapping by restricting or prohibiting manure imports to such regions. The FO 2017 already prescribes and allows to introduce additional measures in regions that exceed target values regarding N in groundwater bodies and P in surface waters. Measures such as lowering the N surplus from 50 to 40 kg ha^{-1} or compulsory manure testing discourage manure imports and lower their negative impacts.

The upcoming revision of the FO in 2020 focuses on extending the measures for areas exceeding NO_3^- target concentrations, which enlarges the possibilities to limit the negative effects of manure imports. The discussed measures are not assessed in this thesis, but the findings give insights on possible effects. They will likely realize a large NO_3^- leaching reduction and especially the reduction of the N target value will play a major role. In large parts of north and west NRW, NO_3^- target concentrations are exceeded (ELWAS-WEB 2019) and additional measures will be compulsory. As these areas are characterized by intensive livestock production, a high share of farms in NRW will need to additionally adapt to the FO 2020 but likely realize further emission reduction. Policymakers should support the current proposals to realize an additional emission reduction to the FO 2017 and to ensure planning reliability by avoiding future tightening of the FO. However, the replacement of the surplus limitations by the recording of fertilizing activities should be up to debate. Firstly, the better enforcement is arguable as farmers still indicate their fertilizer doses themselves. Recording of farm-specific fertilizer demand at point-of-sale would for example strengthen the enforcement, independent of the use of a balance approach or fertilizing planning. Second, the surface balance approach of the FO is well-established and has been continuously tightened over the last FO revisions. Ending such a central measures of the FO might be a fatal signal to the farming sector. One can argue that the farm gate balance, which will become obligatory for more farms after transition periods, can step in for the surface balance approach of the FO 2017. To do so, the allowed surplus of the farm gate balance has to be reduced as it is currently very high. It is however difficult to harmonize a revision of the FO and the directive on the farm gate balance as they are separated in the political process.

Finally, the question arises if more fundamental policy changes should be considered to meet existing environmental targets or future more ambitious reduction goals. Regarding the nutrient management of farms, taxation of nutrient input or surplus as an economic instrument is frequently discussed (SRU 2015, pp. 344ff.). Transaction costs are seen to be small as the base for the tax is recorded in the context of the FO anyway. However, the revision of the FO 2017, as well as the upcoming revision in 2020, reduce the legal nutrient surpluses and limit the chemical fertilizer use by stricter fertilizing planning. The incentive effect of an economic instrument additional to the FO can therefore only take effect in very small ranges. Completely replacing existing nutrient application thresholds by a taxation scheme is most likely not in line with the Nitrates Directive, following the Dutch experience with the mineral accounting system MINAS (Ondersteijn *et al*. 2002, pp. 284f.). Furthermore, fixed surplus limitations are necessary to meet environmental targets which exist area-wide such as the NO_3^- concentration in groundwater bodies. Therefore, the contribution of economic instruments needs further assessments in the context of the existing regulatory framework, taking not only its incentive but also the financing effect into account. Generated financial resources could be used for improved advisory services on nutrient management and better enforcement schemes. Generally, decisions on more fundamental policy changes should be considered after a further careful assessment, including the already realized environmental benefits of the FO 2017 and 2020 and estimating the remaining reduction need. The methodology applied in this thesis can contribute ex-ante and ex-post analysis on the economic and environmental impact of alternative measures to support policy decisions in the future.

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Appendix of Thesis

Appendix Chapter 3

Appendix 3.A Farm specialization according to standard output

Particular type of farming		Farm type explanations	Definition
1		Special field crops	General cropping i.e. cereals, dried pulses and protein crops for the production of grain, oilseeds, potatoes, sugar beet, industrial plants, fresh vegetables, melons, strawberries open field, arable land seed and seedlings, other arable land, bare land and forage for sale > 2/3
	151	Specialist cereals (other than rice) oilseeds and protein crops	Cereals, excluding rice, oilseeds, dried pulses and protein crops > 2/3
	161	Specialist root crops	Potatoes, sugar beet and fodder roots and brassicas > 2/3
	162	Cereals, oilseeds, protein crops and root crops combined	Cereals, oilseeds, dried pulses protein crops > 1/3; roots > 1/3
	166	Various field crops combined	Holdings in class 16, excluding those in 161, 162, 163, 164 and 165 (Fresh vegetables, melons and strawberries open field, Tobacco and Cotton)
4		Specialist grazing livestock	Forage for grazing livestock (i.e. fodder roots and brassicas, plants harvested green, pasture and meadows, rough grazings) and grazing livestock (i.e. equidae, all types of cattle, sheep and goats) > 2/3
	450	Specialist dairying	Dairy cows > 3/4 of total grazing livestock; grazing livestock > 1/3 of grazing livestock and forage
	460	Specialist cattle — rearing and fattening	All cattle (i.e. bovine animals under one year, bovine animals over one but under two and bovine animals two years old and over (male, heifers, dairy cows and other cows)) > 2/3 of grazing livestock; dairy cows ≤ 1/10 of grazing livestock; grazing livestock > 1/3 of grazing livestock and forage
	470	Cattle — dairying, rearing and fattening combined	All cattle > 2/3 of grazing livestock; dairy cows > 1/10 of grazing livestock; grazing livestock > 1/3 of grazing livestock and forage; excluding those holdings in class 45
5		Specialist granivores	Granivores i.e.: Pigs (i.e. piglets, breeding sows, other pigs), poultry (i.e. broilers, laying hens, other poultry) and rabbits breeding females > 2/3
	511	Specialist pig rearing	Breeding sows > 2/3
	512	Specialist pig fattening	Piglets and other pigs > 2/3
	513	Pig rearing and fattening combined	Holdings in class 51, excluding those in classes 511 and 512
7		Mixed livestock holdings	Grazing livestock and forage and granivores > 2/3; grazing livestock and forage ≤ 2/3; granivores ≤ 2/3
	731	Mixed livestock, mainly dairying	Cattle, dairying > 1/3 of grazing livestock; dairy cows > 1/2 of dairying cattle
	732	Mixed livestock, mainly non-dairying grazing livestock	Holdings in class 73, excluding those in class 731
	741	Mixed livestock: granivores and dairying	Cattle, dairying > 1/3 of grazing livestock; granivores > 1/3, dairy cows > 1/2 of cattle, dairying
	742	Mixed livestock: granivores and non-dairying grazing livestock	Holdings in class 74, excluding those in class 741
8		Mixed crops — livestock	Holdings excluded from classes 1 to 7

Particular type of farming	Farm type explanations	Definition
831	Field crops combined with dairying	Cattle, dairying > 1/3 of grazing livestock; dairy cows > 1/2 of cattle, dairying; cattle, dairying < general cropping
832	Dairying combined with field crops	Cattle, dairying > 1/3 of grazing livestock; dairy cows > 1/2 of cattle, dairying; cattle, dairying ≥ general cropping
842	Permanent crops and grazing livestock combined	Permanent crops > 1/3; grazing livestock and forage > 1/3

Source: European Commission (2008, p. 14–19)

Appendix 3.B Results on farm importance

Farm types[a]	Share of farm area	Share of farm numbers	Share of livestock units	Share of dairy cows	Share of fattening pigs	Number of farms
151_<50_>0.2	0.36%	0.76%	0.11%	0.00%	0.01%	256
151_<50_0	3.80%	8.09%	0.04%	0.00%	0.01%	2725
151_>200_0	-	0.20%	-	-	-	67
151_100-200_0	2.35%	0.76%	0.03%	-	-	255
151_50-100_>0.2	0.24%	0.15%	0.07%	-	0.01%	49
151_50-100_0	2.90%	1.78%	0.04%	-	0.02%	600
161_<50_0	0.41%	0.71%	0.00%	-	-	240
161_100-200_0	0.75%	0.24%	-	-	-	82
161_50-100_0	0.41%	0.25%	0.00%	-	0.00%	85
162_<50_0	0.92%	1.37%	0.01%	-	-	461
162_>200_0	-	0.14%	-	0.00%	-	46
162_100-200_0	1.21%	0.38%	0.01%	0.00%	0.00%	127
162_50-100_0	1.38%	0.83%	0.01%	-	-	280
166_<50_>0.2	0.20%	0.28%	0.08%	-	0.06%	93
166_<50_0	2.70%	6.88%	0.01%	0.00%	0.01%	2317
166_>200_0	1.69%	0.21%	0.01%	0.00%	-	71
166_100-200_>0.2	0.50%	0.16%	0.24%	0.08%	-	54
166_100-200_0	2.02%	0.63%	0.03%	0.01%	-	211
166_50-100_>0.2	0.60%	0.34%	0.24%	-	0.17%	116
166_50-100_0	1.58%	0.97%	0.02%	-	0.01%	326
450_<20_>3	0.05%	0.23%	0.39%	1.18%	-	76
450_<20_0-1	0.07%	0.23%	0.04%	0.11%	-	79
450_<20_1-2	0.18%	0.54%	0.21%	0.58%	-	182
450_<20_2-3	0.11%	0.32%	0.21%	0.57%	-	109
450_>100_>3	0.48%	0.15%	1.37%	4.10%	-	50
450_>100_0-1	0.84%	0.25%	0.56%	1.52%	-	84
450_>100_1-2	4.71%	1.45%	5.50%	15.47%	-	487
450_>100_2-3	1.90%	0.57%	3.52%	10.16%	-	192
450_20-50_>3	0.44%	0.51%	1.35%	3.68%	-	171
450_20-50_0-1	0.33%	0.39%	0.19%	0.52%	-	133
450_20-50_1-2	1.37%	1.62%	1.61%	4.37%	-	547
450_20-50_2-3	0.82%	0.94%	1.55%	4.22%	-	316
450_50-100_>3	0.91%	0.57%	2.71%	7.54%	0.14%	192

Farm types[a]	Share of farm area	Share of farm numbers	Share of livestock units	Share of dairy cows	Share of fattening pigs	Number of farms
450_50-100_0-1	0.80%	0.46%	0.52%	1.45%	0.00%	156
450_50-100_1-2	5.10%	3.03%	6.06%	17.04%	0.04%	1022
450_50-100_2-3	2.62%	1.59%	4.94%	13.85%	0.06%	535
460_<20_>3	0.16%	1.30%	1.19%	-	-	438
460_<20_0-1	0.65%	2.18%	0.35%	0.00%	-	734
460_<20_1-2	0.78%	2.78%	0.85%	-	-	936
460_<20_2-3	0.21%	0.96%	0.40%	-	-	324
460_>100_1-2	0.53%	0.16%	-	-	-	53
460_20-50_>3	0.20%	0.26%	0.72%	-	0.03%	88
460_20-50_0-1	1.06%	1.44%	0.58%	-	0.00%	486
460_20-50_1-2	1.30%	1.69%	1.44%	-	0.01%	570
460_20-50_2-3	0.37%	0.46%	0.69%	-	0.02%	155
460_50-100_>3	0.22%	0.15%	0.67%	-	-	49
460_50-100_0-1	0.65%	0.42%	0.36%	-	-	141
460_50-100_1-2	0.91%	0.58%	1.01%	-	-	196
460_50-100_2-3	0.46%	0.28%	0.88%	-	-	94
470_<20_>3	0.02%	0.16%	0.17%	0.15%	0.00%	54
470_<20_1-2	0.08%	0.24%	0.09%	0.09%	-	81
470_<20_2-3	0.05%	0.17%	0.10%	0.12%	-	57
470_20-50_0-1	0.11%	0.14%	0.06%	0.06%	0.00%	48
470_20-50_1-2	0.34%	0.43%	0.39%	0.54%	0.01%	145
470_20-50_2-3	0.13%	0.16%	0.25%	0.34%	0.02%	55
470_50-100_1-2	0.55%	0.33%	0.64%	0.91%	-	110
470_50-100_2-3	0.28%	0.18%	0.53%	0.72%	-	59
511_<20_>3	-	0.53%	-	0.00%	-	179
511_20-50_>3	-	0.34%	-	-	0.07%	113
511_20-50_1-2	-	0.33%	-	0.00%	0.03%	111
511_20-50_2-3	-	0.48%	-	0.00%	0.06%	162
511_50-100_1-2	-	0.34%	-	-	-	113
511_50-100_2-3	-	0.25%	-	-	-	83
512_<20_>3	0.08%	3.85%	8.52%	-	26.15%	1296
512_<20_1-2	0.09%	0.28%	0.11%	0.00%	0.33%	93
512_<20_2-3	0.08%	0.25%	0.16%	0.00%	0.49%	85
512_>100_1-2	-	0.51%	-	-	-	173
512_20-50_>3	0.37%	0.47%	1.10%	-	3.50%	158
512_20-50_1-2	0.63%	0.75%	0.80%	-	2.49%	254
512_20-50_2-3	0.92%	1.07%	1.80%	-	5.79%	361
512_50-100_1-2	-	1.26%	-	0.00%	8.99%	423
512_50-100_2-3	-	0.96%	-	-	8.63%	322
513_>100_1-2	-	0.13%	-	0.00%	-	45
513_20-50_>3	0.11%	0.13%	0.35%	-	0.63%	44
513_20-50_1-2	0.19%	0.23%	0.23%	-	0.41%	76
513_20-50_2-3	0.25%	0.29%	0.49%	-	0.89%	98
513_50-100_1-2	-	0.44%	-	-	-	148
513_50-100_2-3	-	0.38%	-	0.00%	-	129
731_<50_1-2	0.13%	0.18%	0.15%	0.24%	0.09%	62

Farm types[a]	Share of farm area	Share of farm numbers	Share of livestock units	Share of dairy cows	Share of fattening pigs	Number of farms
731_<50_2-3	0.11%	0.14%	0.21%	0.32%	0.20%	48
732_<50_0-1	0.10%	0.21%	0.05%	0.00%	0.03%	72
732_<50_1-2	0.13%	0.25%	0.16%	-	0.10%	84
732_<50_2-3	0.12%	0.18%	0.22%	-	0.21%	61
741_50-100_2-3	-	0.13%	-	-	-	45
742_<50_>3	0.08%	0.14%	0.25%	-	0.36%	48
742_<50_1-2	0.22%	0.36%	0.26%	-	0.36%	122
742_<50_2-3	0.18%	0.25%	0.34%	-	0.58%	83
742_100-200_1-2	0.39%	0.13%	0.44%	-	-	45
742_50-100_1-2	0.48%	0.28%	0.57%	0.00%	1.06%	95
742_50-100_2-3	0.37%	0.23%	0.68%	-	1.26%	79
831_<50_0-1	0.13%	0.20%	0.05%	0.10%	-	66
831_50-100_0-1	0.31%	0.19%	0.14%	0.33%	-	65
832_50-100_0-1	0.25%	0.15%	0.15%	0.40%	0.00%	50
841_<50_0-1	0.64%	1.07%	0.33%	-	0.74%	362
841_<50_1-2	0.30%	0.42%	0.29%	0.00%	0.73%	141
841_>150_0-1	1.35%	0.28%	0.68%	-	1.76%	93
841_100-150_0-1	1.08%	0.38%	0.55%	-	1.34%	128
841_100-150_1-2	0.67%	0.23%	0.64%	-	1.80%	78
841_50-100_0-1	1.37%	0.81%	0.75%	-	1.74%	272
841_50-100_1-2	0.90%	0.52%	0.94%	0.00%	2.51%	176

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [a] code refers to specialization (Appendix 3.A)_size in ha_stocking density in LU ha^{-1}

Appendix 3.C Results on farm characteristics

Farm type[a]	LU total	Dairy cows [LU]	Pig [LU]	Sows [LU]	Arable land [ha]	Grassland [ha]	Livestock density [LU ha^{-1}]
151_<50_>0.2	7.00	0.00	0.00	0.00	14.00	3.00	0.36
151_<50_0	0.00	0.00	0.00	0.00	14.96	0.50	0.00
151_>200_0	0.00	0.00	0.00	0.00	233.50	4.89	0.00
151_100-200_0	0.00	0.00	0.00	0.00	119.11	3.00	0.00
151_50-100_>0.2	23.75	0.00	0.00	0.00	55.20	13.86	0.32
151_50-100_0	0.00	0.00	0.00	0.00	62.40	1.96	0.00
161_<50_0	0.00	-	0.00	0.00	19.90	0.00	0.00
161_100-200_0	0.00	-	0.00	0.00	120.28	1.19	0.00
161_50-100_0	0.00	-	0.00	0.00	65.07	0.00	0.00
162_<50_0	0.00	0.00	0.00	-	27.95	0.13	0.00
162_>200_0	0.00	0.00	0.00	-	231.63	1.12	0.00
162_100-200_0	0.00	0.00	0.00	-	128.20	0.95	0.00
162_50-100_0	0.00	0.00	0.00	-	67.30	0.36	0.00
166_<50_>0.2	11.30	0.00	0.00	0.00	24.50	3.29	0.38
166_<50_0	0.00	0.00	0.00	0.00	6.00	5.01	0.00

Farm type[a]	LU total	Dairy cows [LU]	Pig [LU]	Sows [LU]	Arable land [ha]	Grassland [ha]	Livestock density [LU ha^{-1}]
166_>200_0	0.00	0.00	0.00	0.00	261.29	3.80	0.00
166_100-200_>0.2	57.57	0.00	0.00	0.00	116.95	10.36	0.43
166_100-200_0	0.00	0.00	0.00	0.00	123.02	3.00	0.00
166_50-100_>0.2	29.49	0.00	0.00	0.00	60.13	8.92	0.42
166_50-100_0	0.00	0.00	0.00	0.00	60.53	2.28	0.00
450_<20_>3	51.98	30.00	0.00	0.00	1.89	3.22	4.80
450_<20_0-1	9.30	6.00	0.00	0.00	3.30	8.38	0.69
450_<20_1-2	21.13	13.00	0.00	0.00	3.92	8.50	1.52
450_<20_2-3	37.70	22.00	0.00	0.00	6.82	6.25	2.44
450_>100_>3	476.85	315.00	0.00	0.00	80.74	47.14	3.42
450_>100_0-1	109.00	65.00	0.00	0.00	63.10	71.49	0.88
450_>100_1-2	196.30	125.00	0.00	0.00	53.81	79.19	1.49
450_>100_2-3	300.50	193.00	0.00	0.00	74.04	54.52	2.31
450_20-50_>3	143.98	84.00	0.00	0.00	26.50	9.94	3.72
450_20-50_0-1	27.90	16.00	0.00	0.00	8.25	23.89	0.80
450_20-50_1-2	51.20	31.00	0.00	0.00	13.59	20.80	1.47
450_20-50_2-3	91.33	56.00	0.00	0.00	22.08	13.99	2.36
450_50-100_>3	244.35	147.50	0.00	0.00	48.10	17.87	3.55
450_50-100_0-1	60.35	36.00	0.00	0.00	27.98	42.76	0.87
450_50-100_1-2	104.60	67.00	0.00	0.00	24.24	44.07	1.51
450_50-100_2-3	165.30	106.00	0.00	0.00	41.76	26.00	2.36
460_<20_>3	30.92	0.00	0.00	0.00	0.00	1.51	4.50
460_<20_0-1	8.20	0.00	0.00	0.00	0.00	10.43	0.72
460_<20_1-2	16.20	0.00	0.00	0.00	0.87	7.05	1.38
460_<20_2-3	19.20	0.00	0.00	0.00	2.67	4.27	2.39
460_>100_1-2	183.80	0.00	0.00	0.00	97.30	28.24	1.40
460_20-50_>3	131.85	0.00	0.00	0.00	26.08	3.90	3.90
460_20-50_0-1	21.40	0.00	0.00	0.00	0.28	24.24	0.74
460_20-50_1-2	43.80	0.00	0.00	0.00	15.89	15.09	1.37
460_20-50_2-3	80.10	0.00	0.00	0.00	24.90	5.50	2.34
460_50-100_>3	231.22	0.00	0.00	0.00	58.19	2.01	3.40
460_50-100_0-1	48.80	0.00	0.00	0.00	10.29	51.80	0.74
460_50-100_1-2	89.18	0.00	0.00	0.00	37.99	25.98	1.36
460_50-100_2-3	165.63	0.00	0.00	0.00	58.85	7.91	2.44
470_<20_>3	32.68	6.00	0.00	0.00	0.00	2.43	4.15
470_<20_1-2	20.40	4.00	0.00	0.00	3.88	8.02	1.50
470_<20_2-3	33.90	8.00	0.00	0.00	6.67	5.63	2.38
470_20-50_0-1	22.15	3.50	0.00	0.00	5.39	23.68	0.72

Farm type[a]	LU total	Dairy cows [LU]	Pig [LU]	Sows [LU]	Arable land [ha]	Grassland [ha]	Livestock density [LU ha^{-1}]
470_20-50_1-2	48.90	15.00	0.00	0.00	17.46	14.13	1.45
470_20-50_2-3	79.20	24.00	0.00	0.00	24.26	9.75	2.34
470_50-100_1-2	107.65	31.00	0.00	0.00	37.15	28.25	1.54
470_50-100_2-3	157.40	55.00	0.00	0.00	47.33	14.52	2.37
511_<20_>3	106.00	0.00	0.12	86.70	0.00	0.00	4.63
511_20-50_>3	134.10	0.00	0.24	114.00	30.00	0.50	4.10
511_20-50_1-2	62.22	0.00	0.24	45.00	36.10	0.70	1.69
511_20-50_2-3	86.29	0.00	0.24	64.35	33.65	0.76	2.44
511_50-100_1-2	108.18	0.00	0.24	81.60	63.00	1.22	1.60
511_50-100_2-3	148.72	0.00	0.36	115.50	57.05	1.71	2.35
512_<20_>3	106.54	0.00	103.26	0.00	0.00	0.00	4.60
512_<20_1-2	22.47	0.00	21.48	0.00	12.67	0.30	1.61
512_<20_2-3	33.90	0.00	31.20	0.00	12.74	0.00	2.49
512_>100_1-2	179.76	0.00	177.84	0.00	116.49	2.31	1.47
512_20-50_>3	117.80	0.00	114.00	0.00	31.04	0.00	3.40
512_20-50_1-2	56.40	0.00	54.00	0.00	33.58	0.68	1.64
512_20-50_2-3	93.60	0.00	92.40	0.00	36.00	0.00	2.46
512_50-100_1-2	118.44	0.00	117.60	0.00	71.00	1.00	1.68
512_50-100_2-3	149.82	0.00	148.32	0.00	61.67	0.35	2.30
513_>100_1-2	180.24	0.00	106.08	64.50	118.74	1.50	1.50
513_20-50_>3	140.62	0.00	78.00	43.35	32.83	0.60	3.87
513_20-50_1-2	53.57	0.00	28.20	17.55	33.42	0.96	1.63
513_20-50_2-3	92.91	0.00	51.00	25.05	37.21	1.05	2.44
513_50-100_1-2	116.53	0.00	64.02	37.35	71.90	1.12	1.66
513_50-100_2-3	144.52	0.00	87.84	45.00	60.23	0.90	2.27
731_<50_1-2	43.18	15.00	7.44	0.00	20.44	7.91	1.46
731_<50_2-3	79.18	24.00	22.14	0.00	24.31	8.22	2.54
732_<50_0-1	9.38	0.00	0.00	0.00	8.53	5.92	0.71
732_<50_1-2	29.86	0.00	2.22	0.00	13.97	4.95	1.41
732_<50_2-3	73.60	0.00	18.48	0.00	23.40	2.00	2.44
741_50-100_2-3	177.44	36.00	98.76	0.00	58.24	12.50	2.47
742_<50_>3	107.50	0.00	43.86	0.00	22.61	1.05	3.62
742_<50_1-2	33.05	0.00	11.76	0.00	18.03	3.51	1.43
742_<50_2-3	78.60	0.00	40.80	0.00	27.85	2.00	2.48
742_100-200_1-2	178.16	0.00	132.00	0.00	109.32	11.00	1.42
742_50-100_1-2	105.92	0.00	71.04	0.00	62.72	6.00	1.53
742_50-100_2-3	159.30	0.00	89.88	0.00	61.70	3.88	2.27
831_<50_0-1	13.40	5.00	0.00	0.00	18.98	6.00	0.51
831_50-100_0-1	38.60	21.00	0.00	0.00	53.48	12.19	0.55

Farm type[a]	LU total	Dairy cows [LU]	Pig [LU]	Sows [LU]	Arable land [ha]	Grassland [ha]	Livestock density [LU ha^{-1}]
832_50-100_0-1	52.05	32.00	0.00	0.00	52.31	18.42	0.73
841_<50_0-1	14.02	0.00	7.20	0.00	21.28	0.68	0.64
841_<50_1-2	37.78	0.00	27.72	0.00	30.00	0.16	1.19
841_>150_0-1	132.33	0.00	118.56	0.00	185.88	3.91	0.69
841_100-150_0-1	82.32	0.00	64.02	0.00	115.00	2.45	0.69
841_100-150_1-2	144.00	0.00	135.90	0.00	120.51	0.82	1.19
841_50-100_0-1	48.78	0.00	38.40	0.00	69.33	0.88	0.73
841_50-100_1-2	93.45	0.00	82.20	0.00	70.57	1.00	1.27

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [a] code refers to specialization (Appendix 3.A)_size in ha_stocking density in LU ha^{-1}

Appendix 3.D Results on farm location

Farm type[a]	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191	Number of farms
151_<50_>0.2	1.56%	5.86%	2.34%	30.47%	23.44%	2.34%	6.64%	22.27%	5.08%	256
151_<50_0	1.72%	5.06%	5.47%	25.61%	18.83%	6.72%	10.02%	22.68%	3.89%	2725
151_>200_0	2.99%	8.96%	14.93%	31.34%	32.84%	2.99%	1.49%	0.00%	4.48%	67
151_100-200_0	9.02%	5.88%	16.08%	24.71%	26.67%	0.78%	4.31%	7.84%	4.71%	255
151_50-100_>0.2	10.20%	8.16%	4.08%	30.61%	26.53%	6.12%	6.12%	4.08%	4.08%	49
151_50-100_0	2.67%	6.83%	9.00%	32.83%	21.67%	3.33%	6.83%	12.50%	4.33%	600
161_<50_0	0.00%	0.42%	33.33%	49.58%	0.83%	2.92%	2.92%	9.58%	0.42%	240
161_100-200_0	0.00%	0.00%	64.63%	31.71%	0.00%	1.22%	1.22%	1.22%	0.00%	82
161_50-100_0	0.00%	1.18%	63.53%	31.76%	0.00%	0.00%	1.18%	1.18%	1.18%	85
162_<50_0	0.00%	0.65%	60.30%	24.51%	6.29%	0.43%	3.47%	3.47%	0.87%	461
162_>200_0	0.00%	0.00%	52.17%	30.43%	13.04%	0.00%	2.17%	0.00%	2.17%	46
162_100-200_0	0.00%	0.00%	67.72%	20.47%	7.87%	0.00%	3.15%	0.00%	0.79%	127
162_50-100_0	0.00%	0.71%	67.86%	19.29%	5.36%	0.36%	3.21%	1.07%	2.14%	280
166_<50_>0.2	0.00%	3.23%	30.11%	37.63%	13.98%	0.00%	5.38%	6.45%	3.23%	93
166_<50_0	3.45%	14.29%	6.60%	25.33%	14.11%	3.50%	3.88%	24.56%	4.27%	2317
166_>200_0	1.41%	0.00%	43.66%	22.54%	12.68%	1.41%	11.27%	4.23%	2.82%	71
166_100-200_>0.2	1.85%	3.70%	25.93%	50.00%	9.26%	0.00%	1.85%	3.70%	3.70%	54
166_100-200_0	1.42%	2.37%	34.12%	29.38%	15.17%	2.37%	3.79%	9.00%	2.37%	211
166_50-100_>0.2	1.72%	1.72%	35.34%	39.66%	10.34%	1.72%	0.86%	6.03%	2.59%	116
166_50-100_0	2.76%	4.91%	23.62%	34.05%	12.88%	2.76%	4.60%	11.04%	3.37%	326
450_<20_>3	0.00%	5.26%	10.53%	21.05%	7.89%	3.95%	2.63%	44.74%	3.95%	76
450_<20_0-1	8.86%	32.91%	1.27%	11.39%	12.66%	8.86%	6.33%	12.66%	5.06%	79
450_<20_1-2	4.40%	24.18%	4.95%	17.03%	10.44%	4.40%	1.65%	26.92%	6.04%	182
450_<20_2-3	0.92%	7.34%	2.75%	18.35%	7.34%	6.42%	1.83%	54.13%	0.92%	109
450_>100_>3	0.00%	0.00%	6.00%	62.00%	0.00%	0.00%	0.00%	32.00%	0.00%	50
450_>100_0-1	17.86%	28.57%	4.76%	11.90%	20.24%	3.57%	3.57%	4.76%	4.76%	84

Farm type[a]	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191	Number of farms
450_>100_1-2	12.32%	23.82%	8.01%	19.30%	19.51%	4.11%	2.05%	7.60%	3.29%	487
450_>100_2-3	3.65%	13.54%	3.65%	43.75%	8.85%	1.04%	2.60%	21.88%	1.04%	192
450_20-50_>3	1.17%	0.58%	4.68%	29.24%	1.75%	0.58%	1.17%	60.23%	0.58%	171
450_20-50_0-1	11.28%	37.59%	3.76%	15.04%	9.77%	4.51%	3.76%	4.51%	9.77%	133
450_20-50_1-2	3.66%	30.35%	6.58%	20.11%	14.26%	2.01%	0.37%	19.38%	3.29%	547
450_20-50_2-3	0.95%	8.54%	8.23%	28.48%	6.33%	1.90%	0.63%	43.67%	1.27%	316
450_50-100_>3	0.00%	1.04%	7.29%	44.79%	0.52%	0.52%	0.52%	44.79%	0.52%	192
450_50-100_0-1	19.23%	28.85%	3.85%	7.69%	23.72%	2.56%	1.28%	5.13%	7.69%	156
450_50-100_1-2	5.28%	34.93%	5.38%	19.86%	18.69%	1.57%	0.98%	9.88%	3.42%	1022
450_50-100_2-3	0.56%	10.84%	7.29%	37.38%	5.98%	0.75%	0.37%	36.26%	0.56%	535
460_<20_>3	1.83%	5.25%	4.79%	23.29%	8.22%	0.68%	2.05%	51.14%	2.74%	438
460_<20_0-1	8.58%	46.73%	0.95%	6.95%	16.21%	1.77%	0.95%	15.94%	1.91%	734
460_<20_1-2	4.70%	26.60%	0.96%	13.35%	15.60%	2.56%	1.60%	30.98%	3.63%	936
460_<20_2-3	3.09%	4.94%	2.78%	20.06%	10.80%	3.70%	1.85%	51.54%	1.23%	324
460_>100_1-2	0.00%	7.55%	5.66%	24.53%	13.21%	5.66%	9.43%	32.08%	1.89%	53
460_20-50_>3	0.00%	0.00%	3.41%	21.59%	2.27%	3.41%	2.27%	64.77%	2.27%	88
460_20-50_0-1	8.02%	41.15%	2.67%	11.32%	14.40%	1.44%	0.82%	17.08%	3.09%	486
460_20-50_1-2	1.58%	23.51%	1.58%	19.65%	11.75%	2.46%	3.16%	32.81%	3.51%	570
460_20-50_2-3	0.65%	7.74%	1.29%	24.52%	5.16%	1.94%	3.87%	52.90%	1.94%	155
460_50-100_>3	0.00%	0.00%	0.00%	22.45%	2.04%	0.00%	2.04%	73.47%	0.00%	49
460_50-100_0-1	12.77%	29.79%	2.84%	14.89%	18.44%	0.71%	1.42%	16.31%	2.84%	141
460_50-100_1-2	3.57%	23.47%	0.51%	27.04%	10.71%	2.55%	3.57%	23.47%	5.10%	196
460_50-100_2-3	0.00%	4.26%	2.13%	28.72%	4.26%	3.19%	1.06%	52.13%	4.26%	94
470_<20_>3	0.00%	14.81%	5.56%	18.52%	1.85%	1.85%	0.00%	53.70%	3.70%	54
470_<20_1-2	4.94%	13.58%	2.47%	14.81%	16.05%	6.17%	0.00%	38.27%	3.70%	81
470_<20_2-3	1.75%	5.26%	1.75%	17.54%	5.26%	1.75%	1.75%	59.65%	5.26%	57
470_20-50_0-1	8.33%	43.75%	0.00%	10.42%	12.50%	8.33%	0.00%	12.50%	4.17%	48
470_20-50_1-2	0.69%	14.48%	1.38%	22.07%	13.10%	3.45%	4.83%	35.86%	4.14%	145
470_20-50_2-3	0.00%	9.09%	1.82%	16.36%	1.82%	1.82%	0.00%	69.09%	0.00%	55
470_50-100_1-2	3.64%	15.45%	5.45%	21.82%	18.18%	4.55%	2.73%	25.45%	2.73%	110
470_50-100_2-3	0.00%	1.69%	1.69%	25.42%	1.69%	0.00%	3.39%	62.71%	3.39%	59
511_<20_>3	0.56%	5.03%	0.00%	29.05%	6.70%	2.79%	3.91%	49.72%	2.23%	179
511_20-50_>3	0.00%	0.88%	0.88%	30.97%	1.77%	6.19%	2.65%	54.87%	1.77%	113
511_20-50_1-2	0.00%	2.70%	2.70%	36.94%	4.50%	1.80%	0.00%	47.75%	3.60%	111
511_20-50_2-3	0.00%	1.23%	1.23%	31.48%	5.56%	1.85%	0.62%	55.56%	2.47%	162

Farm type[a]	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191	Number of farms
511_50-100_1-2	0.00%	4.42%	0.00%	27.43%	7.96%	5.31%	7.08%	46.90%	0.88%	113
511_50-100_2-3	0.00%	7.23%	0.00%	30.12%	7.23%	6.02%	2.41%	45.78%	1.20%	83
512_<20_>3	0.00%	3.86%	1.00%	37.50%	6.79%	2.55%	2.62%	43.90%	1.77%	1296
512_<20_1-2	1.08%	1.08%	0.00%	27.96%	1.08%	3.23%	3.23%	61.29%	1.08%	93
512_<20_2-3	0.00%	2.35%	0.00%	41.18%	2.35%	1.18%	1.18%	51.76%	0.00%	85
512_>100_1-2	0.00%	8.09%	0.58%	35.26%	24.28%	2.89%	2.31%	21.97%	4.62%	173
512_20-50_>3	0.00%	1.90%	0.63%	38.61%	1.27%	2.53%	1.27%	52.53%	1.27%	158
512_20-50_1-2	0.00%	3.15%	0.00%	41.34%	6.30%	5.51%	3.94%	37.01%	2.76%	254
512_20-50_2-3	0.00%	2.22%	0.00%	39.89%	4.16%	2.22%	2.77%	46.81%	1.94%	361
512_50-100_1-2	0.24%	6.86%	0.47%	33.10%	15.37%	4.26%	4.96%	32.15%	2.60%	423
512_50-100_2-3	0.62%	2.80%	0.00%	39.44%	5.28%	3.42%	1.55%	44.41%	2.48%	322
513_>100_1-2	0.00%	13.33%	2.22%	17.78%	26.67%	11.11%	4.44%	20.00%	4.44%	45
513_20-50_>3	0.00%	2.27%	0.00%	38.64%	2.27%	2.27%	2.27%	52.27%	0.00%	44
513_20-50_1-2	0.00%	6.58%	0.00%	43.42%	6.58%	9.21%	3.95%	30.26%	0.00%	76
513_20-50_2-3	0.00%	4.08%	0.00%	37.76%	2.04%	3.06%	1.02%	52.04%	0.00%	98
513_50-100_1-2	0.00%	4.73%	1.35%	35.14%	10.14%	13.51%	4.73%	27.70%	2.70%	148
513_50-100_2-3	0.00%	0.00%	1.55%	36.43%	6.20%	5.43%	0.78%	44.96%	4.65%	129
731_<50_1-2	0.00%	9.68%	0.00%	29.03%	14.52%	6.45%	6.45%	30.65%	3.23%	62
731_<50_2-3	0.00%	0.00%	0.00%	31.25%	0.00%	0.00%	0.00%	68.75%	0.00%	48
732_<50_0-1	1.39%	13.89%	5.56%	26.39%	19.44%	2.78%	4.17%	23.61%	2.78%	72
732_<50_1-2	1.19%	9.52%	0.00%	22.62%	11.90%	0.00%	2.38%	46.43%	5.95%	84
732_<50_2-3	0.00%	3.28%	0.00%	19.67%	4.92%	1.64%	1.64%	63.93%	4.92%	61
741_50-100_2-3	0.00%	0.00%	0.00%	40.00%	2.22%	0.00%	0.00%	55.56%	2.22%	45
742_<50_>3	2.08%	2.08%	0.00%	18.75%	4.17%	0.00%	2.08%	64.58%	6.25%	48
742_<50_1-2	0.00%	7.38%	1.64%	30.33%	8.20%	3.28%	1.64%	44.26%	3.28%	122
742_<50_2-3	0.00%	2.41%	1.20%	33.73%	1.20%	0.00%	0.00%	59.04%	2.41%	83
742_100-200_1-2	0.00%	2.22%	0.00%	33.33%	8.89%	13.33%	2.22%	33.33%	6.67%	45
742_50-100_1-2	0.00%	6.32%	1.05%	34.74%	2.11%	4.21%	8.42%	37.89%	5.26%	95
742_50-100_2-3	0.00%	0.00%	1.27%	27.85%	1.27%	1.27%	0.00%	67.09%	1.27%	79
831_<50_0-1	3.03%	9.09%	18.18%	18.18%	19.70%	3.03%	3.03%	19.70%	6.06%	66
831_50-100_0-1	6.15%	3.08%	41.54%	21.54%	16.92%	1.54%	3.08%	3.08%	3.08%	65
832_50-100_0-1	6.00%	4.00%	32.00%	18.00%	30.00%	2.00%	2.00%	4.00%	2.00%	50
841_<50_0-1	0.00%	5.25%	1.66%	27.90%	15.19%	9.12%	8.01%	29.83%	3.04%	362
841_<50_1-2	0.00%	0.71%	2.84%	43.26%	5.67%	4.26%	3.55%	39.01%	0.71%	141
841_>150_0-1	0.00%	7.53%	1.08%	22.58%	36.56%	5.38%	11.83%	10.75%	4.30%	93
841_100-150_0-1	0.78%	3.13%	4.69%	33.59%	28.91%	4.69%	4.69%	16.41%	3.13%	128

Farm type[a]	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191	Number of farms
841_100-150_1-2	0.00%	6.41%	1.28%	46.15%	6.41%	6.41%	6.41%	21.79%	5.13%	78
841_50-100_0-1	0.00%	6.25%	4.41%	30.88%	21.69%	8.46%	9.93%	15.81%	2.57%	272
841_50-100_1-2	0.00%	5.68%	2.84%	36.93%	6.82%	4.55%	2.27%	39.77%	1.14%	176

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; a code refers to specialization (Appendix 3.A)_size in ha_stocking density in LU ha-1, SCR - soil-climate region

Appendix 3.E Results on crop rotations

Specialization[c]	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191
151	WW WB WR[b]	WW WB WR[a]	WW WB WR[a]	WW WB WR[a]	WW WB WR[a]	-	WW WB WR[a]	WW KM KM[a]	WW WB WR[a]
161	-	--	WW WW SB[b]	WW WB SB[b]	-	-	-	-	-
162	WW WW SB[a]	-	WW WW SB[a]	WW WW SB[a]	-	-	-	-	-
166	WW WB SB[b]	-	WW WB SM[a]	WW WB SM[a]	WW WB SM[a]	WTr WB SM SM[a]	WW WB SM[a]	WW SM SM[a]	-
450	WW SG SM[a]	WW SM SM[a]	WW SM SB[b]	WW SM SM[a]	WW WB SM[b]	-	WW WB SM[a]	-	-
460	WW SG WTr[b]	-	WW SM SM[b]	WW WB SM SM[a]	WW WB SM SM[b]	WTr WB SM SM[a]	-	WTr SM SM[a]	-
470	WW SM WW WTr[b]	-	WW SM[b]	WW SM SM[a]	WW WB SM SM[b]	-	-	WTr WB SM SM[a]	WW WTr SM SM[a]
511	-	-	WW B SB[b]	WW WB CCM[b]	WW WB WR[b]	WTr WB CCM[a]	-	WTr WB CCM SM[a]	-
512	-	-	WW WB SB[b]	WW WB CCM[a]	WW WB WTr WR[b]	-	-	WW WB CCM CCM[a]	-
513	-	-	WW WB SB[a]	WW WB CCM[a]	WW WB WR[b]	-	-	WTr WB CCM CCM[a]	-
731	-	WW WB	-	-	-		-	WW WB	-

Specialization[c]	SCR 129	SCR 134	SCR 141	SCR 142	SCR 143	SCR 146	SCR 147	SCR 148	SCR 191
		SM[a]						CCM SM[a]	
732	-	-	-	-	WW WB SM[a]	-	-	WTr WB SM SM[a]	-
741	-	-	-	-	-		-	WW WB CCM SM[a]	-
742	-	-	-	WW WB CCM SM[a]	-	WW WTr CCM SM[a]	-	WTr WB CCM SM[a]	-
831	WW WB WW WR[b]	-	WW SM WW SB[a]	WW WB SM SB[b]	WG WB SM[b]	-	-	WW WB SM SM[b]	-
832	WW WB WW WR[a]	-	WW SM WW SB[b]	WW WB SM SB[b]	WW WB WW WR[b]	-	-	WB CCM CCM SM[b]	-
833	WW SG WR[a]	-	WW WB SM SB[a]	WW WB SM[a]	-	-	-	WTr WB CCM SM[a]	WW WB SM[a]
834	-	WWTr WR SM[a]	WW WB SB[b]	WW WB SM[a]	-	-	-	WTr WB CCM SM[a]	WW WB SM[a]
841	-	-	-	WW WB WW CCM[a]	WW WB WR[a]	-	WW WB WR[a]	WTr WB CCM SM[a]	-

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation (crop rotations marked with a), RDC of the Federal Statistical Office and Statistical Offices of the Laender, Census of Agriculture, 2010, own calculation (crop rotations marked with b), Gaiser (2018); c code refers to specialization (Appendix 3.A); CCM - corn-cob-mix; KM - grain maize; WB - winter barley; WR/WRa - winter rapeseed; WTr - winter triticale; WW - winter wheat; SB - sugar beet; SCR - soil-climate region; SM - silage maize; Tr - triticale

Appendix 3.F References

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Appendix Chapter 4

Appendix 4.A Ammonia emission factors for manure application depending on techniques and speed of manure incorporation

Manure application technique and incorporation	kg NH_3-N (kg TAN)$^{-1}$
Broadcast without incorporation in vegetation	0.25
Broadcast with incorporation ≤ 8	0.13
Broadcast with incorporation ≤ 4	0.09
Trailing hose without incorporation in vegetation	0.175
Trailing hose with incorporation ≤ 8	0.0925
Trailing hose with incorporation ≤ 4	0.06

Source: Haenel et al. (2018, p. 189) and Döhler et al. (2002, p. 73); N - nitrogen, NH_3 - ammonia, TAN - total ammonia nitrogen

Appendix 4.B Important input-output coefficients of FarmDyn

Coefficient	Value	Coefficient	Value
Costs manure export (€ m^{-3})	12	N content imported manure (kg m^{-3})	5.22
Pork meat price (€ kg^{-1})	1.67	P_2O_5 content imported manure (kg m^{-3})	3.33
Piglet price (€ $head^{-1}$)	48.2	N content winter wheat (kg (100 kg yield) $^{-1}$)	2.11
Winter wheat price (€ t^{-1})	159	N content winter barley (kg (100 kg yield) $^{-1}$)	1.79
Winter barley price (€ t^{-1})	151	N content corn cob mix (kg (100 kg yield) $^{-1}$)	1.05
Rapeseed price (€ t^{-1})	347	N content sugar beet (kg (100 kg yield) $^{-1}$)	0.18
Cereal straw price (€ t^{-1})	70	N content winter rapeseed (kg (100 kg yield) $^{-1}$)	3.35
Feed soybean meal price (€ t^{-1})	338	P_2O_5 content winter wheat (kg (100 kg yield) $^{-1}$)	0.80
Feed soybean oil price (€ t^{-1})	1150	P_2O_5 content winter barley (kg (100 kg yield) $^{-1}$)	0.80
Feed rapeseed meal price (€ t^{-1})	220	P_2O_5 content corn cob mix (kg (100 kg yield) $^{-1}$)	0.53
Feed plant fat price (€ t^{-1})	1000	P_2O_5 content sugar beet (kg (100 kg yield) $^{-1}$)	0.10
Feed mineral price (€ t^{-1})	700	P_2O_5 content winter rapeseed (kg (100 kg yield) $^{-1}$)	1.80
Diesel price (€ l^{-1})	0.7	Manure Silo 500 m^3 (€ m^{-3} a^{-1})	6.62
Chemical N fertilizer price (€ kg^{-1})	0.29	Manure Silo 1500 m^3 (€ m^{-3} a^{-1})	3.06
Chemical P_2O_5 fertilizer price (€ kg^{-1})	0.24	Manure Silo 3000 m^3 (€ m^{-3} a^{-1})	2.26
Fattener N excretion N-P reduced (kg $head^{-1}$ a^{-1})	11.7	Manure Silo 5000 m^3 (€ m^{-3} a^{-1})	1.82
Fattener P_2O_5 excretion N-P reduced (kg $head^{-1}$ a^{-1})	4.4	Costs manure broadcast spread (€ m^{-3})	1.74
Fattener N excretion strongly N-P reduced (kg $head^{-1}$ a^{-1})	10.06	Costs manure trailing hose applied (€ m^{-3})	2.80
Fattener P_2O_5 excretion strongly N-P reduced (kg $head^{-1}$ a^{-1})	3.9		

Source: FarmDyn parameters; € - Euro; N – nitrogen; P_2O_5 – phosphate; P – phosphorus

Appendix 4.C Exemplary fertilizer scenarios for silage maize and winter wheat

Silage Maize			Winter Wheat		
Chemical Fertilizer (kg N ha^{-1})	Manure (kg N ha^{-1})		Chemical Fertilizer (kg N ha^{-1})	Manure (kg N ha^{-1})	
	Spring	Autumn		Spring	Autumn
7.8	0.0	0.0	39.9	0.0	0.0
20.0	32.2	60.0	50.0	20.0	60.0
40.0	40.0	72.2	60.0	30.0	72.2
60.0	52.2	80.0	69.9	40.0	80.0
79.2	72.2		80.0	50.0	
79.9	80.0		89.9	60.0	
100.0	92.2		100.0	80.0	
119.9	96.2		110.0	100.0	
139.9	112.2		119.9	110.0	
159.9	120.0		139.9	120.0	
180.0	132.2		150.0	140.0	
200.0	140.0		159.9	160.0	
240.0	152.2		172.8	180.0	
	160.0		180.0		
	172.2		200.0		
	192.2		219.9		
	200.0				
	232.2				

Amount (in kg ha^{-1}) and source (chemical fertilizer and manure) of nitrogen application in silage maize and winter wheat used to create 108 fertilizer scenarios in regions 141, 142 & 148, as input for the scenario simulations with the SIMPLACE framework. Manure can be applied two times (i.e., in spring and in autumn), whereas, the application of chemical fertilizer was related to specific growth stages depending on the respective crop; N - nitrogen

Appendix 4.D Establishment of crop parameters and metrices used as a measure of systematic bias between the observed and simulated value (i.e., mean residual and mean relative error)

As a starting point to establish a parameter sets for the crops subject to further adjustments and later calibration, the default crop parameter dataset for Lintul5 is used, which is mostly similar or identical to the crop parameters in the WOFOST model (Boogard *et al.* 1998; Boons-Prins *et al.* 1993). TSUM1 (thermal time requirement from emergence to anthesis) and TSUM2 (thermal time requirement from anthesis to maturity) are fixed to values obtained from phenology and daily temperature observations. The remaining parameters are used for calibration. To do so, first, a plausible range for each parameter is obtained from the literature (Ceglar *et al.* 2011; Boons-Prins *et al.* 1993). Next, SIMPLACE runs are performed on draws constructed by systematic sampling from these parameter ranges. These runs are evaluated by comparing the simulated grain yield and the phenology to the corresponding observations and the draw with the smallest mean residual error (ME) chosen. The parameters in that draw are the basis for the simulation results used in the study.

The ME as a measure to select the best set of parameters, based on a comparison of the statistical data and simulated values, is defined as follows (Papula 1982):

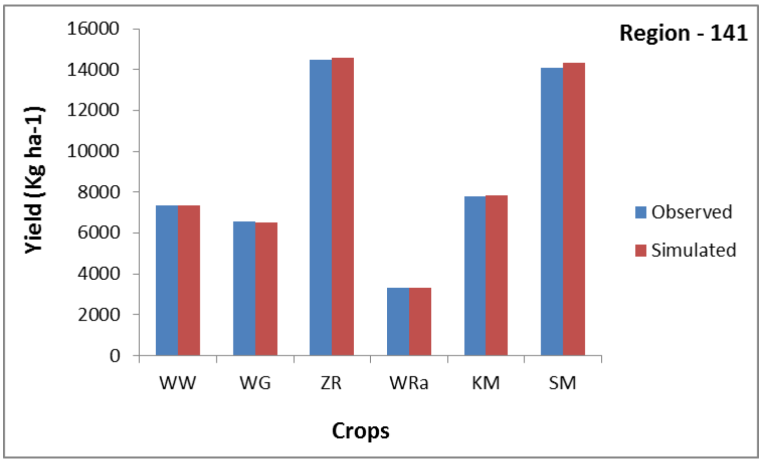
$$ME = \frac{1}{n}\sum_{i=1}^{n} y_i - x_i \qquad \text{…………… Eq. 1}$$

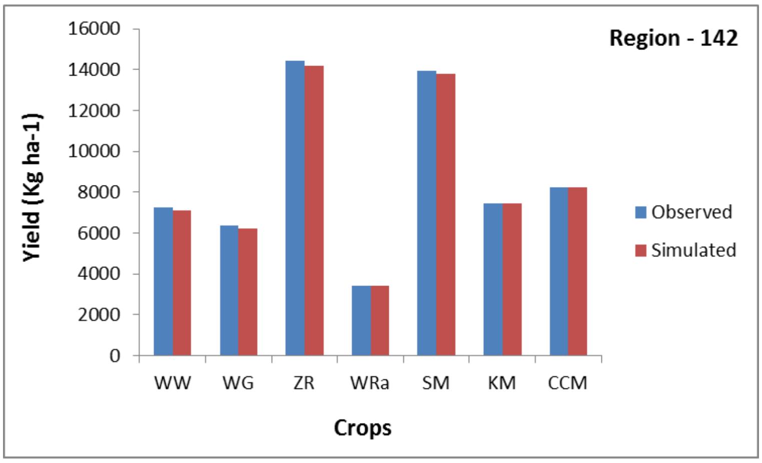
We also report mean relative error (MR) as:

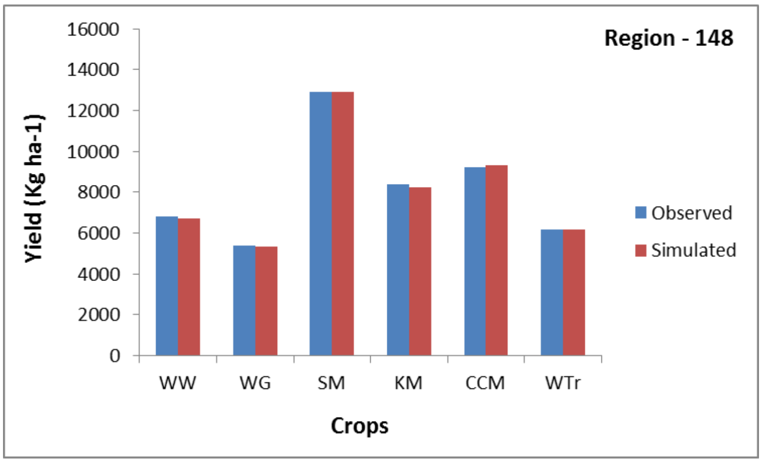
$$MR = \frac{1}{n}\sum_{i=1}^{n} \frac{(y_i - x_i)}{x_i} \qquad \text{…………… Eq. 2}$$

Where n is the sample number, x is the observed and y is the simulated value. A value of 0 of ME indicates no systematic bias between simulated and measured values in absolute term, whereas in case of the MR, differences are normalized by the observations. In both cases, small values indicate little difference between simulated and measured values.

Appendix 4.E Simulated (nutrient limited) versus observed (statistics) crops) yield averaged over 1999-2008 in the regions 141, 142 and 148 respectively in North Rhine -Westphalia (NRW)

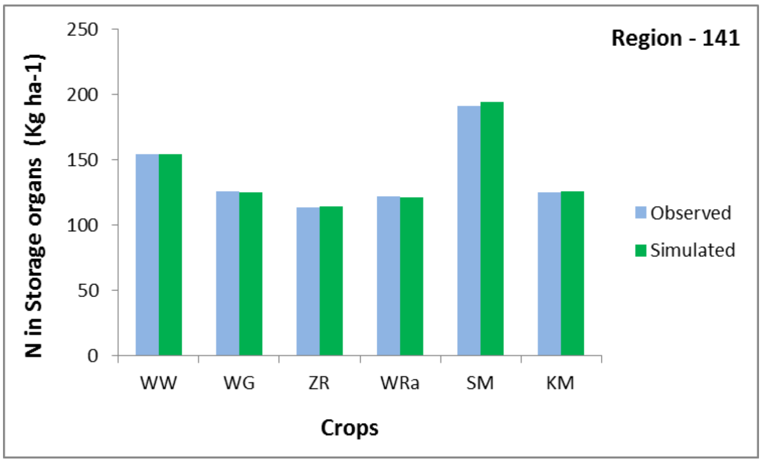


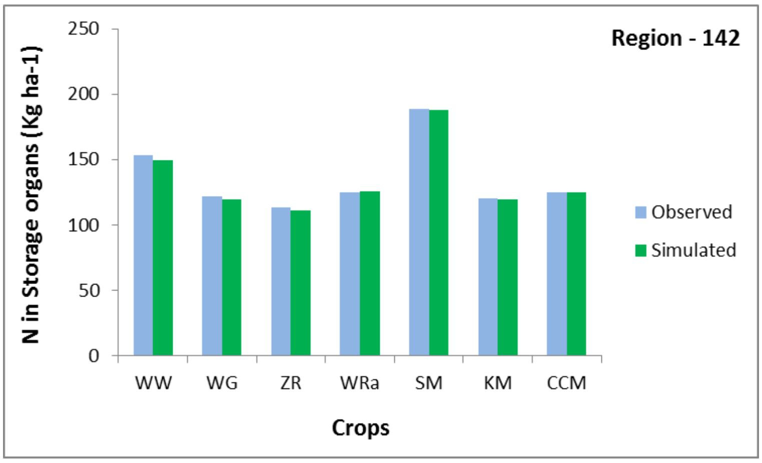


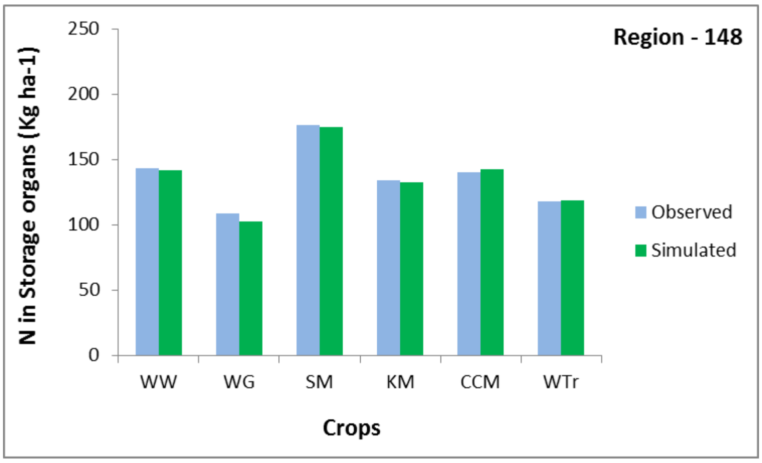


WW - winter wheat; WG - winter barley; ZR - sugar beet; WRa - winter rapeseed; KM - corn maize; SM - silage maize; CCM - maize for corn-cob-mix; WTr - winter triticale

Appendix 4.FSimulated versus observed nitrogen in storage organs of crops (kg ha^{-1}) averaged over 1999-2008 in the regions 141, 142 and 148 respectively in North Rhine -Westphalia (NRW)







WW - winter wheat; WG - winter barley; ZR - sugar beet; WRa - winter rapeseed; KM - corn maize; SM - silage maize; CCM - maize for corn-cob-mix; WTr - winter triticale

Appendix 4.G Mean Relative Error (MR, in %) and Mean Residual Error (ME, kg ha^{-1}) of crop yields and nitrogen uptake in storage organs (NSO, kg ha^{-1}) in the regions 141, 142 and 148 in North Rhine -Westphalia (NRW)

Region	Crop	MR (%)		ME (kg ha^{-1})	
		Yield	NSO	Yield	NSO
141	WW	0.003	-0.001	0.2	-0.001
	WG	-0.6	-1.1	-41.6	-1.4
	ZR	0.7	1.3	108.0	1.5
	WRa	-0.3	-0.8	-9.4	-0.9
	KM	0.3	0.2	23.6	0.3
	SM	1.5	1.6	206.1	3.0
142	WW	-1.8	-2.3	-133.4	-3.5
	WG	-1.8	-1.8	-115.2	-2.2
	ZR	-1.5	-1.5	-213.2	-1.7
	WRa	0.9	0.6	29.1	0.8
	SM	-0.8	-0.7	-114.6	-1.3
	KM	-0.2	-0.6	-13.7	-0.8
	CCM	0.3	0.2	23.7	0.2
148	WW	-1.2	-1.1	-85.1	-1.5
	WG	-0.5	-5.8	-27.6	-6.3
	SM	-0.2	-0.8	-30.8	-1.4
	KM	-1.3	-1.0	-107.7	-1.3
	CCM	1.5	1.7	135.1	2.4
	WTr	0.5	0.5	30.7	0.6

WW - winter wheat; WG - winter barley; ZR - sugar beet; WRa - winter rape; KM - corn maize; SM - slage maize; CCM – maize for corn-cob-mix; WTr - winter triticale

Appendix 4.H References

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Appendix Chapter 5

Appendix 5.A Statistical meta-model to assess the sensitivity of compliance costs to exogenous variables and assumptions

To assess the sensitivity of the results to exogenous variables and assumptions, the sampling and modelling procedure is repeated with additional variables. The selected variables are either linked to the costs of different compliance strategies or assumptions with regard to the fertilizer management. We derive plausible ranges for the variables from literature, as seen in the following table, assuming uniform distributions as empirical distributions linked to specific farm characteristics are not available. The correlation between all factors is assumed to be zero which also reduces the danger of multicollinearity in the statistical meta-model. We repeat the sampling procedure and the farm modelling for samples of 10,000 pig and dairy farms, respectively. The result matrices are used to run multiple linear regression models, separately for dairy and pig production.

Table Appendix 5.A Additional explanatory variables for the statistical meta-model

Explanatory factors	Minimum	Default value	Maximum
Pork price [€ (kg carcase weight)$^{-1}$]	1.30[1]	1.44[1]	1.60[1]
Milk price [€ (kg ECM)$^{-1}$]	0.29[1]	0.32[1]	0.37[1]
Straw price [€ t^{-1}]	70.00[1]	115.00[1]	190.00[1]
Manure export costs [€ m^{-3}]	1.00[2]	12.00[2]	20.00[2]
Manure application costs [€ m^{-3}]	trailing hose 1.80[3]	trailing hose 2.80[4]	trailing hose 3.58[3]
	trailing shoe 1.92[3]	trailing shoe 3.01[4]	trailing shoe 3.85[3]
	injection 2.30[3]	injection 3.90[4]	injection 5.00[3]
Minimum chemical fertilizer need [kg ha^{-1}a^{-1}]	maize: 0 kg P_20_5 0 kg N	maize: 20 kg P_20_5[5] 8 kg N[5]	maize: 40 kg P_20_5 16 kg N
	winter wheat: 0 kg N	winter wheat: 40 kg N[5]	winter wheat: 80 kg N
	winter barley: 0 kg N	winter barley: 40 kg N[5]	winter barley: 80 kg N
	sugar beet: 0 kg N	sugar beet: 30 kg N[5]	sugar beet: 60 kg N
Mineral fertilizer equivalents [%]	-	pig manure 0.7[6]	pig manure 0.8[6]
	-	cattle manure 0.6[6]	cattle manure 0.7[6]

Sources: [1] KTBL (2016, pp. 265, 509, 653); [2] Appendix 5.G; [3] Noordhof (2018), Assumption made that highest and lowest named prices refer to the technology with the highest or lowest default price, respectively. Price of other technologies is adapted in accordance; [4] Kuratorium für Betriebshilfsdienste und Maschinenringe in Westfalen-Lippe e.V. (2017, p. 6) and KTBL (2018); [5] Gaiser (2018); [6] BMEL (2017, pp. 5, 22); [7] LWK SH (2018, p. 119); € - Euro; ECM - energy-corrected milk; N - nitrogen; P_2O_5 - phosphate

The statistical meta-model returns the impact of prices, exogenous to the model, and crucial assumption on the compliance costs with the FO 2017. Pork prices have a significant increasing effect on the compliance costs, a rise of pork prices of 1 € (kg carcass weight)$^{-1}$

increases compliance costs by 0.33 € pig^{-1}. The reason is that some pig farms lower their stocking numbers to meet nutrient application thresholds, especially those facing high costs to export manure. Lowering the pig stock is costlier when pig prices are high. Furthermore, farms having a stocking density slightly above 3 LU ha^{-1} reduce stocking density to avoid investment in additional manure storage capacity. The latter effect is also present for dairy farms; however, the meta-model does not return a significant impact of milk prices on compliance costs.

As expected, the meta-model shows that manure export costs drive compliance costs. This effect is highly significant for pig farms as the export of manure is a core strategy to comply with the stricter manure application thresholds of the FO 2017. However, only around 15% of pig farms need to adapt to these thresholds and, hence, the average cost increase is relatively low (0.0085 € pig^{-1} for a rise of manure export costs of 1 € m^{-3}). Dairy farms which exceed 3 LU ha^{-1} and export manure under the FO 2007 reduce stocking density when they face very high export costs (15 to 20 € m^{-3}) because production becomes unprofitable in combination with the need to invest into additional storage capacity. Therefore, manure export costs significantly impact on compliance costs for dairy farms in the meta-model.

The costs for low-emission manure application techniques strongly influence compliance costs as the now obligatory use of these technologies is a main cost driver, especially for dairy farms. A rise of the application costs by 1 € m^{-3} increase compliance costs on average by 0.18 ct (kg ECM)$^{-1}$. On pig farms, a rise of 1 € m^{-3} increases compliance costs by 0.06 € pig^{-1}.

For pig and dairy farms, assumptions about minimum necessary chemical fertilizer application to crops have a significant effect on compliance cost. They determine to which extent chemical fertilizer is always applied in addition to manure N and P_2O_5 and, hence, influence N and P_2O_5 surpluses. Thus, compliance costs increase when assuming higher minimum chemical fertilizer doses. The effect is especially strong on pig farms as all crops grown, in contrast to grassland, are assumed to require some chemical fertilizer. Here, assumptions for maize are especially relevant for pig farm as firstly maize is a relevant crop on the pig farms in the sample and, secondly, the typically starter fertilization in maize comprises 20 kg P_2O_5 ha^{-1}. The amount of that starter fertilization strongly drives the P_2O_5 surplus restrictions which are most limiting for manure application on pig farms. 1 kg additional chemical fertilizer increases compliance costs by 0.07 € pig^{-1}. Dairy farms, which have a high share of arable land and face high minimum chemical fertilizer need, have to export manure due to the strict P_2O_5 surplus restriction. Likewise, the compliance costs of dairy farms are significantly increased by assumed higher minimum chemical fertilizer needs.

The fertilizing planning under the FO 2017 specifies MFE for manure N, which farmers have to consider. However, farmers can account for higher MFE due to optimal management, which is captured exemplary in the meta-model. Higher MFE lead to a significant reduction of compliance costs for pig farms. Increasing MFE by 1% lowers compliance costs by 0.005 € pig^{-1} on average. It is linked to the costs for farms to fulfill the 0 kg P_2O_5 surplus restrictions in combination with high stocking density. In this case, farms mostly adapt by exporting manure to lower P_2O_5 surpluses. As N and P_2O_5 are combined in manure, manure N which is needed for plant nutrition leaves the farm likewise. This is driven by a divergence of the N:P_2O_5 relation of crop nutrient need and manure (Schröder 2005, p. 257). Higher MFE lead to a convergence of the N:P_2O_5 ratios and lowers the costs for chemical N fertilizer needed to compensate for exported manure.

Appendix 5.B Assumptions for creating farm data from the Farm Structure Survey (FSS)

Farm Size

Farm size in ha is directly derived from the FSS, using the variable agricultural land (variable code C0240).

Grassland Share

Grassland share is directly derived from the FSS. The arable land (C0210) is subtracted from the total agricultural land (C0240). The amount of grassland is divided by the total agricultural land (C0240).

Stocking density

Stocking density is directly derived from the FSS. The total amount of LU (C3391) is divided by the total agricultural land (C0240).

Manure storage capacity

The manure storage capacity is taken from Osterburg & Techen (2012, p. 176) which derive the data from the FSS 2007. They specify the amount of LU which are kept in farms with a certain manure storage capacity in months. We assume that this distribution corresponds to the distribution of manure storage capacity at farm-level. Furthermore, we assume that farms which held manure storage capacities of 2 to 4 months in 2007 increased their capacity to 6 months by now as required by regulations before the 2017 revision of the FO.

Low-emission application techniques

The use of low-emission application techniques is introduced as a binary variable. The FSS specifies the amount of manure which is applied with a certain technology on a certain type of land (C2321 to C2344). We assume that the low emission manure application techniques are available on a farm if more than 25% of the total manure is applied with such technologies.

P-enriched soils

The soil P status is available at regional level related based on data from Jacobs (2014). This data is coupled to the FSS. Every farm is related to regions based on the county in which it is located in. The location of farms is included in the FSS at community level (ASE). We assume that the distribution of P soil status at land area and farm-level is equal. Every farm receives a relative value for the share of farms with P-enriched soils in the region the farm is located in. Relating the relative value of farms with P-enriched soils to the total farm numbers in a region allows deriving the total and share of dairy and pig farms with P-enriched soils in the whole sample.

Appendix 5.C Correlation coefficients for farm characteristics on pig farms

	Farm Size	Stocking Density	Manure Storage Capacity	Low-emission application techniques	P-enriched soils
Farm Size	-	-0.1459[1]	-0.1115[2]	0.3216[1]	
Stocking Density		-	-0.0284[2]	-0.0276[1]	0.3[3]
Manure Storage Capacity			-		
Low-emission application techniques				-	
P-enriched soils					-

Pearson's correlation coefficient; [1] Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [2] Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Agricultural census, 2010, own calculation; [3] assumed based on regional data from Osterburg & Techen (2012, p. 201)

Appendix 5.D Correlation coefficients for farm characteristics on dairy farms

	Farm Size	Grassland share	Stocking Density	Manure Storage Capacity	Low-emission application techniques	P-enriched soils
Farm Size	-	-0.0322[1]	-0.0796[1]	0.0764[2]	0.2042[1]	
Grassland share		-	-0.1015[1]	-0.0067[2]	0.0782[1]	
Stocking Density			-	-0.0294[2]	-0.1859[1]	0.3[3]
Manure Storage Capacity				-		
Low-emission application techniques					-	
P-enriched soils						-

Pearson's correlation coefficient; [1] Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation; [2] Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Agricultural census, 2010, own calculation; [3] assumed based on regional data from Osterburg & Techen (2012, p. 201)

Appendix 5.E Percentiles of characteristics of specialized pig farms

	Farm Size [ha]	Stocking density [LU ha^{-1}]	Manure storage capacity [m]	P-enriched soils [1/0]	Low-emission application techniques [1/0]
p1	6.84	1.11	6.00	0	0
p2	6.84	1.11	6.00	0	0
p3	7.63	1.16	6.00	0	0
p4	8.62	1.20	6.00	0	0
p5	10.21	1.23	6.00	0	0
p6	11.42	1.26	6.00	0	0
p7	12.60	1.29	6.00	0	0
p8	14.16	1.32	6.00	0	0
p9	15.03	1.35	6.00	0	0
p10	16.50	1.37	6.00	0	0
p11	17.48	1.39	6.00	0	0
p12	18.00	1.42	6.00	0	0
p13	19.22	1.44	6.00	0	0
p14	20.00	1.45	6.00	0	0
p15	21.28	1.47	6.00	0	0
p16	22.00	1.49	6.00	0	0
p17	22.77	1.50	6.00	0	0
p18	23.90	1.52	6.00	0	0
p19	24.75	1.54	6.00	0	0
p20	25.31	1.56	6.00	0	0
p21	26.08	1.57	6.00	0	0
p22	27.00	1.59	6.00	0	0
p23	28.00	1.61	6.00	0	0
p24	29.19	1.62	6.00	0	0
p25	29.92	1.64	6.00	0	0

	Farm Size [ha]	Stocking density [LU ha^{-1}]	Manure storage capacity [m]	P-enriched soils [1/0]	Low-emission application techniques [1/0]
p26	30.59	1.65	6.00	0	0
p27	31.27	1.67	6.00	0	0
p28	32.14	1.68	6.00	0	0
p29	32.81	1.70	6.00	0	0
p30	33.38	1.71	6.00	0	0
p31	34.00	1.73	6.00	0	0
p32	34.91	1.74	6.00	0	0
p33	35.79	1.77	6.00	0	0
p34	36.56	1.78	6.00	1	0
p35	37.63	1.79	6.00	1	0
p36	38.22	1.81	6.00	1	0
p37	38.90	1.83	6.00	1	0
p38	39.44	1.84	6.00	1	0
p39	40.06	1.85	6.00	1	0
p40	40.61	1.87	6.00	1	0
p41	41.65	1.89	6.00	1	0
p42	42.35	1.91	6.00	1	0
p43	43.37	1.92	6.00	1	0
p44	44.10	1.94	6.00	1	0
p45	44.83	1.95	6.00	1	0
p46	45.33	1.98	8.00	1	0
p47	45.99	2.00	8.00	1	0
p48	46.59	2.02	8.00	1	0
p49	47.56	2.04	8.00	1	0
p50	48.20	2.06	8.00	1	0
p51	48.94	2.07	8.00	1	0
p52	49.94	2.09	8.00	1	1
p53	50.52	2.12	8.00	1	1
p54	51.13	2.14	8.00	1	1
p55	52.00	2.16	8.00	1	1
p56	52.70	2.18	8.00	1	1
p57	53.79	2.20	8.00	1	1
p58	54.50	2.21	8.00	1	1
p59	55.25	2.24	8.00	1	1
p60	56.14	2.25	8.00	1	1
p61	57.00	2.28	8.00	1	1
p62	58.00	2.30	8.00	1	1
p63	59.42	2.32	8.00	1	1
p64	60.28	2.34	8.00	1	1
p65	60.99	2.36	8.00	1	1
p66	61.97	2.38	8.00	1	1
p67	62.64	2.40	8.00	1	1
p68	64.23	2.43	8.00	1	1
p69	65.65	2.46	8.00	1	1
p70	67.00	2.48	8.00	1	1
p71	68.09	2.50	8.00	1	1
p72	69.98	2.53	8.00	1	1
p73	70.99	2.55	8.00	1	1
p74	72.07	2.58	8.00	1	1

	Farm Size [ha]	Stocking density [LU ha^{-1}]	Manure storage capacity [m]	P-enriched soils [1/0]	Low-emission application techniques [1/0]
p75	73.49	2.61	8.00	1	1
p76	74.52	2.64	8.00	1	1
p77	75.81	2.67	8.00	1	1
p78	76.91	2.70	8.00	1	1
p79	77.98	2.74	8.00	1	1
p80	79.35	2.77	8.00	1	1
p81	81.02	2.81	8.00	1	1
p82	82.32	2.85	8.00	1	1
p83	83.76	2.88	8.00	1	1
p84	85.72	2.93	8.00	1	1
p85	87.82	2.98	8.00	1	1
p86	90.00	3.03	8.00	1	1
p87	92.16	3.06	8.00	1	1
p88	94.42	3.12	8.00	1	1
p89	96.77	3.17	8.00	1	1
p90	99.47	3.26	8.00	1	1
p91	102.36	3.32	8.00	1	1
p92	105.12	3.45	8.00	1	1
p93	109.27	3.61	8.00	1	1
p94	114.01	3.81	8.00	1	1
p95	118.00	4.07	8.00	1	1
p96	123.12	4.59	8.00	1	1
p97	129.48	5.47	8.00	1	1
p98	141.01	8.12	8.00	1	1
p99	159.05	14.82	8.00	1	1
p100	159.05	14.82	8.00	1	1

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation. See Section 5.3.1 for further sources. Due to privacy protection requirements, the p1 and p100 cannot be provided. Therefore, we assume that p1 equals p2 and p100 equals p99; LU - livestock units; p - percentile; P - phosphorus

Appendix 5.F Percentiles of characteristics of specialized dairy farms

	Farm Size [ha]	Stocking density [LU ha^{-1}]	Grassland Share [%]	Manure storage capacity [m]	P-enriched soils [1/0]	Low-emission application techniques [1/0]
p1	8.14	0.63	0.06	6.00	0	0
p2	8.14	0.63	0.06	6.00	0	0
p3	10.59	0.71	0.08	6.00	0	0
p4	12.26	0.77	0.10	6.00	0	0
p5	14.00	0.82	0.12	6.00	0	0
p6	15.72	0.85	0.13	6.00	0	0
p7	17.05	0.90	0.14	6.00	0	0
p8	18.23	0.93	0.15	6.00	0	0
p9	19.09	0.96	0.17	6.00	0	0
p10	19.98	0.99	0.18	6.00	0	0
p11	21.80	1.01	0.19	6.00	0	0
p12	23.46	1.03	0.20	6.00	0	0
p13	24.55	1.06	0.21	6.00	0	0

	Farm Size [ha]	Stocking density [LU ha^{-1}]	Grassland Share [%]	Manure storage capacity [m]	P-enriched soils [1/0]	Low-emission application techniques [1/0]
p14	25.67	1.08	0.22	6.00	0	0
p15	27.38	1.11	0.22	6.00	0	0
p16	28.86	1.13	0.24	6.00	0	0
p17	30.00	1.15	0.24	6.00	0	0
p18	31.06	1.17	0.25	6.00	0	0
p19	32.19	1.19	0.26	6.00	0	0
p20	33.34	1.21	0.27	6.00	0	0
p21	34.36	1.22	0.27	6.00	0	0
p22	35.33	1.24	0.28	6.00	0	0
p23	36.26	1.26	0.29	6.00	0	0
p24	37.29	1.28	0.30	6.00	0	0
p25	38.71	1.30	0.31	6.00	0	0
p26	39.75	1.31	0.32	6.00	0	0
p27	40.81	1.33	0.32	6.00	0	0
p28	41.47	1.35	0.33	6.00	0	0
p29	42.60	1.36	0.34	6.00	0	0
p30	43.55	1.38	0.35	6.00	0	0
p31	44.30	1.40	0.35	6.00	0	0
p32	45.26	1.42	0.36	6.00	0	0
p33	46.18	1.44	0.37	6.00	0	0
p34	47.00	1.46	0.37	6.00	0	0
p35	48.00	1.48	0.38	6.00	0	0
p36	49.00	1.49	0.39	6.00	0	0
p37	50.00	1.51	0.40	6.00	0	0
p38	51.00	1.53	0.40	6.00	0	0
p39	52.00	1.55	0.41	6.00	0	0
p40	52.73	1.56	0.42	6.00	0	0
p41	53.45	1.58	0.43	6.00	0	0
p42	54.47	1.60	0.44	6.00	0	0
p43	55.15	1.63	0.45	6.00	0	0
p44	56.00	1.65	0.46	6.00	0	0
p45	56.77	1.66	0.47	6.00	0	0
p46	57.33	1.68	0.48	8.00	0	0
p47	58.55	1.70	0.49	8.00	1	0
p48	59.49	1.71	0.49	8.00	1	0
p49	60.28	1.73	0.50	8.00	1	0
p50	61.24	1.75	0.51	8.00	1	0
p51	61.97	1.77	0.52	8.00	1	0
p52	62.84	1.79	0.53	8.00	1	0
p53	63.81	1.81	0.54	8.00	1	0
p54	64.52	1.83	0.55	8.00	1	0
p55	65.52	1.85	0.56	8.00	1	1
p56	66.39	1.87	0.57	8.00	1	1
p57	67.45	1.89	0.59	8.00	1	1
p58	68.48	1.91	0.60	8.00	1	1
p59	69.31	1.93	0.61	8.00	1	1
p60	70.25	1.95	0.62	8.00	1	1
p61	71.50	1.97	0.63	8.00	1	1
p62	72.50	1.99	0.64	8.00	1	1

	Farm Size [ha]	Stocking density [LU ha^{-1}]	Grassland Share [%]	Manure storage capacity [m]	P-enriched soils [1/0]	Low-emission application techniques [1/0]
p63	73.52	2.02	0.66	8.00	1	1
p64	74.54	2.04	0.67	8.00	1	1
p65	75.32	2.06	0.69	8.00	1	1
p66	76.46	2.09	0.70	8.00	1	1
p67	77.70	2.11	0.71	8.00	1	1
p68	79.12	2.14	0.72	8.00	1	1
p69	80.00	2.17	0.74	8.00	1	1
p70	81.79	2.19	0.75	8.00	1	1
p71	83.19	2.21	0.77	8.00	1	1
p72	84.66	2.24	0.78	8.00	1	1
p73	86.00	2.26	0.79	8.00	1	1
p74	87.90	2.30	0.80	8.00	1	1
p75	89.33	2.33	0.81	8.00	1	1
p76	91.22	2.37	0.82	8.00	1	1
p77	93.25	2.41	0.83	8.00	1	1
p78	94.87	2.44	0.84	8.00	1	1
p79	96.80	2.48	0.86	8.00	1	1
p80	98.20	2.51	0.87	8.00	1	1
p81	100.00	2.55	0.88	8.00	1	1
p82	101.35	2.61	0.89	8.00	1	1
p83	103.35	2.65	0.91	8.00	1	1
p84	106.00	2.69	0.92	8.00	1	1
p85	108.70	2.75	0.93	8.00	1	1
p86	111.28	2.82	0.95	8.00	1	1
p87	113.50	2.88	0.97	8.00	1	1
p88	117.00	2.93	1.00	8.00	1	1
p89	119.69	3.01	1.00	8.00	1	1
p90	123.73	3.08	1.00	8.00	1	1
p91	128.40	3.19	1.00	8.00	1	1
p92	133.00	3.30	1.00	8.00	1	1
p93	137.93	3.45	1.00	8.00	1	1
p94	143.48	3.60	1.00	8.00	1	1
p95	152.43	3.76	1.00	8.00	1	1
p96	161.75	3.90	1.00	8.00	1	1
p97	171.09	4.22	1.00	8.00	1	1
p98	189.77	4.65	1.00	8.00	1	1
p99	221.35	5.94	1.00	8.00	1	1
p100	221.35	5.94	1.00	8.00	1	1

Source: RDC of the Federal Statistical Office and Statistical Offices of the Laender. Farm Structure Survey, 2016, own calculation. See Section 5.3.1 for further sources. Due to privacy protection requirements, p1 and p100 cannot be provided. Therefore, we assume that p1 equals p2 and p100 equals p99; LU - livestock units; p - percentile; P – phosphorus

Appendix 5.G Results on the range of manure export costs

Assumptions on the range of manure export costs are based on grey literature as representative surveys are not available. Online search has been done for selected terms ("Kosten + Gülleexport", "Kosten + Gülleabgabe", "Kosten + Güllebörse") using google.com on August 15th, 2018. The results are summarized in the following table and the found range enters the statistical meta-model. As lowest manure export costs 1 € is assumed to reflect that the used data source on the farm characteristics contains farms which are separated for legal reasons and face very low or no export costs (Chapter 3).

Table Appendix 5.G Results on the range of manure export costs

Source	Costs	Year	Comment
Braun (2015, p. 39)	12 € m^{-3}	2015	-
DLZ Agrarmagazin (2015, p. 7)	10 € m^{-3}	2015	-
Frehe (2018)	Up to 15 € m^{-3}	2018	-
Hartl *et al.* (2013, p. 11)	9 - 11 € m^{-3} 13 - 15 € m^{-3}	2013 2015 (estimate)	-
H & K aktuell (2016, p. 7)	Up to 15 € m^{-3}	2016	-
Neumann (2015)	8 - 12 € m^{-3}	2015	-
Schnippe (2013, pp. 10ff.)	9 - 11 € m^{-3} up to 20 € m^{-3}	2013	High costs under storage shortage in winter
top agrar (2013)	8.50 - 9 € m^{-3}	2013	-

€ - Euro

Appendix 5.H Important Input-Output coefficients of the single farm model Farmdyn

Coefficient	Value	Coefficient	Value
Milk yield (kg milk head^{-1})	9000.00	P excretion pig N-P reduced feed (kg place^{-1})	4.40
Pig meat output (kg head^{-1})	85.90	P excretion pig strongly N-P reduced feed (kg place^{-1})	3.90
Winter wheat yield (t FM ha^{-1})	8.00	Milk price (cent kg^{-1})	32.00
Winter barley yield (t FM ha^{-1})	7.00	Pork price (€ kg^{-1})	1.44
Maize silage yield (t FM ha^{-1})	45.00	Beef price, old cow (€ kg^{-1})	3.10
Maize corn-cob-mix yield (t FM ha^{-1})	14.00	Winter wheat price (€ t^{-1})	204.00
Grass “low intensity” yield (t FM ha^{-1})	16.60	Winter barley price (€ t^{-1})	192.00
Grass “high intensity” yield (f FM ha^{-1})	24.50	Cereal straw (€ t^{-1})	115.00
N content corn winter wheat (kg (100 kg yield) $^{-1}$)	2.11	Maize silage input price (€ t^{-1})	40.00
N content corn winter barley (kg (100 kg yield) $^{-1}$)	1.79	Gras silage input price (€ t^{-1})	56.00
N content corn-cob-mix (kg (100 kg yield)$^{-1}$)	1.05	Concentrate cattle input price 1 (€ t^{-1})	280.00
N content maize silage (kg (100 kg yield) $^{-1}$)	0.38	Concentrate cattle input price 2 (€ t^{-1})	290.00
P content corn winter wheat (kg (100 kg yield) $^{-1}$)	0.80	Concentrate cattle input price 3 (€ t^{-1})	340.00
P content corn winter barley (kg (100 kg yield^{-1})	0.80	Milk powder input price (€ t^{-1})	2460.00
P content corn-cob-mix (kg (100 kg yield) $^{-1}$)	0.53	Oils for feed input price (€ t^{-1})	1150.00
P content maize silage (kg (100 kg yield) $^{-1}$)	0.19	Winter Cereal input price (€ t^{-1})	205.00
N content grass “low intensity” (t FM (100 kg yield) $^{-1}$)	0.64	Winter Barley input price (€ t^{-1})	207.00
N content grass “high intensity” (t FM (100 kg yield) $^{-1}$)	0.84	Soybean meal input price (€ t^{-1})	339.00
P content grass “low intensity” (t FM (100 kg yield) $^{-1}$)	0.36	Soybean oil input price (€ t^{-1})	1150.00
P content grass “high intensity” (t FM (100 kg yield) $^{-1}$)	0.36	Rapeseed meal input price (€ t^{-1})	220.00
N excretion cow (kg head^{-1})	117.00	Plant fat input price ((€ t^{-1})	1000.00
N excretion heifers (kg head^{-1})	48.00	Mineral pig feed (€ t^{-1})	700.00
N excretion calves (kg place^{-1})	16.60	Ammonium sulphate saltpetre (€ kg^{-1})	0.31
N excretion pig standard feed (kg place^{-1})	12.20	Calcium ammonium nitrate (€ kg^{-1})	0.31
N excretion pig N-P reduced feed (kg place^{-1})	11.70	PK fertilizer 18:10 (€ kg^{-1})	0.24
N excretion pig strongly N-P reduced feed (kg place^{-1})	10.60	Lime (€ t^{-1})	59.00
P excretion cow (kg head^{-1})	42.00	Manure Silo 500 m^{3} (€ m^{-3})	6.62
P excretion heifers (kg head^{-1})	15.50	Manure Silo 1500 m^{3} (€ m^{-3})	3.06
P excretion calves (kg place^{-1})	6.40	Manure Silo 3000 m^{3} (€ m^{-3})	2.26
P excretion pig standard feed (kg place^{-1})	5.00	Manure Silo 5000 m^{3} (€ m^{-3})	1.82

Source: FarmDyn parameters; € - Euro; FM - fresh matter; N - nitrogen; P - phosphorus

Appendix 5.I Calculations for result comparison with Karl & Noleppa (2017)

Karl & Noleppa (2017) calculate total compliance costs with the Fertilization Ordinance (FO) 2017 for two average German farms, differentiated by the legal form. To make the results comparable to our findings, the conversions and assumptions summarized in the following table are made.

Table Appendix 5.I Results from Karl & Noleppa (2017) on compliance costs with the Fertilization Ordinance 2017 for two average German farms

Farm type	Farm size [ha]	Stocking density [LU ha^{-1}]	Compliance costs [€ farm^{-1}]	Pigs [heads farm^{-1}]	Compliance costs [€ pig^{-1}]
Private Enterprise	75.70[1]	1.80[1]	2,486.00[2]	851.15[3]	2.92[4]
Legal Entity	1,131,20[1]	1.10[1]	35,937.00[2]	7,805.28[3]	4.60[4]

[1] Values from Karl & Noleppa (2017, p. 3); [2] Values from Karl & Noleppa (2017, pp. 31f.); [3] Own calculation. As Karl & Noleppa (2017) assess average farms, farms have a diverse animal stock. To allow comparison to the study at hand, we assume that all animals are pigs. Number is derived by dividing stocking density [LU ha^{-1}] by the livestock factor for pigs of 0.16 LU pig^{-1} (BMEL 2017, p. 41); [4] own calculation; € - Euro; LU - livestock units

Appendix 5.J Calculations for result comparison with Menghi et al. (2015)

Menghi *et al.* (2015) jointly calculate the compliance costs with the Nitrates Directive and EU Directive of the European Parliament and of the Council concerning integrated pollution prevention and control. Furthermore, they relate costs to 100 kg slaughter weight as we relate costs to one slaughtered pig. To compare the results to our findings, the calculation the following table is done for the European pig farms assessed by Menghi *et al.* (2015).

Table Appendix 5.J Results from Menghi et al. (2015) on compliance costs with the Nitrates Directive for European pig farms

Farm type	Costs with all regulations [€ (100 kg slaughter weight)$^{-1}$]	Relative cost reduction without Nitrates Directive [%]	Absolut costs related to the Nitrates Directive [€ (100 kg slaughter weight)$^{-1}$]	Absolut costs related to the Nitrates Directive [€ pig^{-1}]
Denmark (DK 614)	139.16[1]	0.60[2]	0.83[3]	0.72[3]
Germany (DE 187)	152.76[1]	0.57[2]	0.87[3]	0.75[3]
Netherlands (NL 369)	142.30[1]	0.74[2]	1.05[3]	0.91[3]
Poland (PL 50)	125.66[1]	0[2]	0[3]	0[3]

[1] Values from Menghi et al. (2015, p. 140, Table 4.38); [2] Values from Menghi et al. (2015, p. 144, Table 4.41); [3]Own calculation; assumption of a pig slaughter weight of 86.25 kg KTBL (2016, p. 652); € - Euro

Appendix 5.K References

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Appendix Chapter 6

Appendix 6.A Emission factors and resource use related to impact categories based on ReCiPE v.1.07

	CO_2 [1 kg]	CH_4 [1 kg]	N_2O [1 kg]	NH_3 [1 kg]	NO_x [1 kg]	SO_2 [1 kg]	PM10 [1 kg]	NO_3^- [1 kg]	PO_4 [1 kg]	Gas [1 MJ]	Oil [1 MJ]	Coal [1 MJ]
Global warming potential [kg CO_2eq]	11	25	298									
Terrestrial acidification [kg SO_2eq]				2.45	00.56	1						
Marine eutrophication [kg Neq]				0.092	0.039			0.23				
Freshwater eutrophication [kg Peq]									0.33			
Particulate matter formation [kg PM10eq]				0.32	0.22	0.2	1					
Fossil fuel depletion [kg oil eq]										0.02	0.02	0.02

Source: Goedkoop et al. (2013); CH_4 - methane; CO_2 - carbon dioxide; N_2O - nitrous oxide; NH_3 - ammonia; NO_3^- - nitrate; NO_x - nitrogen oxides; PO_4 - orthophosphate; SO_2 - sulfur dioxide

Appendix 6.B References

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