Analyses on the Mitigation of Environmental Pollution by Nitrogen from Agriculture - Selected Indicators and Regulatory Policy Options to Improve Nutrient Management

Dissertation

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Preface

This doctoral thesis is based on three research papers published in international peer-reviewed journals, which are referred to by their respective Roman numeral throughout the thesis.

Paper I:

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Paper II:

Löw, P. & Osterburg, B. (2023) Evaluation of nitrogen balances and nitrogen use efficiencies on farm level of the German agricultural sector. *Agricultural Systems* (Revised manuscript submitted 14 April 2023).

Paper III:

Löw, P., Karatay, Y. N. & Osterburg, B. (2020) Nitrogen use efficiency on dairy farms with different grazing systems in northwestern Germany. *Environmental Research Communications* Volume 2, Number 10. (Published 2 December 2020) DOI: https://doi.org/10.1088/2515-7620/abccbc

Abstract

Nitrogen (N) supply is essential for sustainable and cost-effective crop production, but losses of reactive N from agricultural activities pose a major ecological threat, with negative impacts on biodiversity, climate, soil fertility, and human health. Germany has national and international targets for lowering N pollution, but these are about to be exceeded. Multiple indicators and calculation methods are used to assess N pollution in agri-environmental contexts, so the indicator value *per se* is not decisive, but robust and informative indicators are needed for policymakers to define targeted N reduction measures. Identification of relevant agri-environmental N indicators for use in national legislation is thus required. This thesis examined selected N indicators related to N management, namely N balance, fertilization planning, and N use efficiency (NUE), to (i) assess the functionality of N-related regulatory approaches embedded in German legislation; (ii) identify robust and meaningful N indicators and current levels for farm types in Germany; and (iii) quantify N flows at farm level and potential for reducing N emissions.

Comparison of three agri-environmental N indicators, as entry points for existing German regulations limiting excess N fertilizer inputs, revealed that design and purpose differ but that data requirements are very similar, although the underlying parameters differ in data reliability and data uncertainty. Farm-gate balancing was the most robust indicator investigated. Maximum N fertilizer input limits based on farm accounting data varied depending on regulatory approach and associated indicators, and defined legal thresholds. Different levels of strictness applied for farm types in Germany.

NUE values, measured as ratio of N outputs to N inputs (derived from parameters in farm-gate N balances), and their determinants for farm types were analyzed based on comprehensive farm data for the German agricultural sector. On average, NUE increased from dairy to pig and poultry, other cattle, and mixed farms, and was highest for arable and permanent crop farms. There was large variation within investigated farm types, indicating efficiency reserves and potential for improving NUE. Significant links were found between NUE and regional, farm structural, and socio-economic characteristics of farms, such as soil and climate conditions, crop selection and diversity, and use of advisory services. Knowledge on determining N performance of farms can support policymakers in designing agri-environmental policies to improve N management, e.g., through advisory work or incentivizing N-efficient crop types.

To determine efficiency reserves, a case study was performed on dairy farms in Northwestern Germany with four different grazing intensities, comparing N balance and NUE on different system scales. As dairy farms showed lowest efficiency of all farm types studied, this analysis enabled identification of potential N inefficiency hotspots. Efficiency reserves were identified for all grazing systems, from full grazing (group 1) to zero grazing (group 4), although farms without pasture access showed slightly better N performance on all system levels (feed, field, farm) studied. The analysis also revealed systematic errors in estimated manure N and forage N amounts in mandatory farm data reporting, necessitating plausibility checks.

Overall, this thesis improved understanding of interactions between N indicators embedded in German legislation and their suitability as regulatory approach. Improved methodology for quantifying relevant N flows based on farm accounting data allowed calculation of relevant N indicators, enabling impact assessments on individual farm N reduction requirements and increased N efficiency. This can help achieve environmental and climate goals defined e.g., in the German Sustainable Development Strategy and Climate Action Program 2030.

Zusammenfassung

Die Versorgung mit Stickstoff (N) ist für eine nachhaltige und kosteneffiziente Nahrungsmittelproduktion unerlässlich, doch die Verluste von reaktivem N infolge landwirtschaftlicher Tätigkeiten stellen eine große ökologische Bedrohung dar, mit negativen Auswirkungen auf die biologische Vielfalt, das Klima, die Bodenfruchtbarkeit und die menschliche Gesundheit. Deutschland hat nationale und internationale Zielsetzungen zur Verringerung der N-Belastung, die jedoch im Begriff sind, überschritten zu werden. Zur Bewertung der N-Belastung im Agrarumweltbereich werden zahlreiche Indikatoren und Berechnungsmethoden verwendet, so dass der Indikatorwert für sich genommen nicht entscheidend ist, aber robuste und aussagekräftige Indikatoren benötigt werden, damit die politischen Entscheidungsträger gezielte Maßnahmen zur N-Reduzierung definieren können. Daher ist es erforderlich, relevante Agrarumweltindikatoren für die Umsetzung in der nationalen Gesetzgebung zu identifizieren.

In dieser Arbeit wurden ausgewählte N-Indikatoren in dem Zusammenhang mit betrieblichem N-Management untersucht, nämlich die N-Bilanz, die Düngeplanung und die N-Nutzungseffizienz (NUE), um (i) die Funktionsweise der in der deutschen Gesetzgebung verankerten regulatorischen Ansätze für N zu bewerten; (ii) robuste und aussagekräftige N-Indikatoren und aktuelle Indikatorwerte verschiedener Betriebstypen in Deutschland zu identifizieren; und (iii) die N-Ströme auf Betriebsebene und das Potenzial zur Minderung von N-Emissionen zu quantifizieren.

Der Vergleich von drei Agrarumweltindikatoren, die als Ansatzstelle für die Regulierung zur Begrenzung eines übermäßigen N-Düngereinsatzes fungieren, hat gezeigt, dass sich Design und Zweck unterscheiden, die Datenanforderungen jedoch sehr ähnlich sind, obwohl sich die zu berücksichtigenden Parameter hinsichtlich der Datenzuverlässigkeit und -unsicherheit unterscheiden. Die Brutto-Hoftorbilanzierung erwies sich als der robusteste der untersuchten N-Indikatoren. Die maximalen N-Düngereinsätze auf der Grundlage von Buchführungsdaten variierten je nach regulatorischem Ansatz und den damit verbundenen Indikatoren sowie den gesetzlich festgelegten Grenzwerten. Für die Betriebstypen in Deutschland ergaben sich unterschiedliche Anforderungen an die N-Minderung.

Die Höhe der NUE-Werte, gemessen als Verhältnis aus N-Abgaben und N-Zufuhren (abgeleitet aus den Parametern der Brutto-Hoftorbilanz), und deren Determinanten für die verschiedenen Betriebstypen wurden auf der Grundlage umfassender Betriebsdaten für den deutschen Agrarsektor analysiert. Im Durchschnitt stieg die NUE von Milchviehbetrieben zu Schweine- und

Geflügelbetrieben, sonstigen Futterbaubetrieben und Gemischtbetrieben an und war am höchsten für Ackerbau- und Dauerkulturbetriebe. Innerhalb der untersuchten Betriebstypen wurden große Varianzen identifiziert, was auf Effizienzreserven und Potentiale zur Verbesserung der NUE hindeutet. Es wurden signifikante Zusammenhänge zwischen der NUE und regionalen, betriebsstrukturellen und sozioökonomischen Merkmalen der Betriebe festgestellt, wie zum Beispiel den Boden- und Klimabedingungen, Auswahl und Vielfalt der Kulturpflanzen sowie Inanspruchnahme von Beratungsleistungen. Das Wissen über diese Zusammenhänge kann politische Entscheidungsträger bei der Gestaltung von Agrarumweltmaßnahmen zur Verbesserung des N-Managements unterstützen, z. B. durch die Förderung von Beratungsdiensten oder durch Anreize für N-effiziente Kulturarten.

Zur Erkennung von Effizienzreserven wurde eine Fallstudie für Milchviehbetriebe in Nordwestdeutschland mit vier verschiedenen Weideintensitäten durchgeführt, wobei N-Bilanz und NUE auf verschiedenen Systemebenen verglichen wurden. Da Milchviehbetriebe im Vergleich zu anderen Betriebstypen die geringste Effizienz aufwiesen, ermöglichte diese Analyse die Identifizierung potenzieller Hotspots für N-Ineffizienzen. Effizienzreserven wurden für alle Weidesysteme identifiziert, vom Vollweidesystem (Gruppe 1) bis zur ganzjährigen Stallhaltung (Gruppe 4), wobei Betriebe ohne Weidezugang auf allen untersuchten Systemebenen (Futter, Feld, Betrieb) eine leicht bessere N-Verwertung aufwiesen. Die Analyse zeigte auch systematische Abweichungen bei der Schätzung innerbetrieblich verwendeter N-Mengen aus Gülle und Futtermittel in den gesetzlich vorgeschriebenen Aufzeichnungspflichten auf, was Plausibilitätsprüfungen erforderlich machte.

Insgesamt trägt diese Arbeit zu einem besseren Verständnis zwischen den in der deutschen Gesetzgebung eingebetteten N-Indikatoren und ihrer Eignung als regulatorischer Ansatz bei. Eine verbesserte Methodik zur Quantifizierung relevanter N-Ströme auf der Grundlage von Buchführungsdaten landwirtschaftlicher Betriebe ermöglichte die Berechnung relevanter N-Indikatoren. Diese ermöglichen die Folgenabschätzungen hinsichtlich betriebsindividueller N-Minderungsbedarfe und die Identifizierung von Möglichkeiten zur Steigerung der N-Effizienz. Dies kann zur Erreichung der Umwelt- und Klimaziele beitragen, die etwa in der Deutschen Nachhaltigkeitsstrategie und im Klimaschutzprogramm 2030 definiert sind.

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List of abbreviations

BMEL Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture)

BMUV Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection)

CAP Common Agricultural Policy

CO2-eq Carbon dioxide equivalent

COM European Commission

DüV Düngeverordnung (Fertilizer Application Ordinance)

EU European Union

EU-MS Member states of the European Union

F2F Farm to Fork

FADN Farm Accountancy Data Network

FarmB Farm-gate nitrogen balance

FaST Farm Sustainability Tool

FertP Fertilization planning

FSDN Farm Sustainability Data Network

LSU Livestock unit

N Nitrogen

NH_4 Ammonium

NO_3 Nitrate

NO_x Oxidized nitrogen

NUE Nitrogen use efficiency

P	Phosphorus
K	Potassium
SoilB	Soil surface nitrogen balance
StoffBilV	Stoffstrombilanzverordnung (Ordinance on Substance Flow Analysis)
UAA	Utilized agricultural area

1 Introduction

1.1 Problem statement and motivation

Nitrogen (N) is an essential macronutrient for plant nutrition and N fertilizers play a key role in agriculture for sustainable and cost-effective crop production, contributing to higher yields, quality standards, and maintained soil fertility. However, once applied, N can react chemically and pass into the environment as a reactive compound in liquid, gaseous, or solid form. Excessive use of mineral fertilizers, in amounts exceeding crop N demand, and regionally high accumulation and application rates of organic fertilizers have led to large N losses to air and water (LWK NI 2022; UBA 2022c). These primarily diffuse N emissions have numerous negative external effects, such as impaired drinking water quality due to increasing nitrate concentrations, pollution of surface waters, oceans, and soils, negative impacts of gaseous emissions on biodiversity and human health (ammonia), and global warming (nitrous oxide) (Sutton & Bleeker 2013; FAO 2018; Erisman 2021). With a growing global population and increasing demand for food (Kanter et al. 2020; United Nations 2022), mankind faces a balancing act between agricultural intensification and reducing negative externalities of agricultural activities.

Optimized N management in agriculture is essential to reduce these negative environmental effects while maintaining agricultural productivity. In this regard, sustainable intensification is a holistic concept that envisages an agricultural transformation embedded in increasing yields and avoiding negative externalities and additional land use (Garnett et al. 2013; Godfray & Garnett 2014; EUNEP 2015). Such transformation is critical in order to combat growing pressures on the global food system, including on the supply side, through increased competition for inputs and climate change, and on the demand side, through rising population and per capita consumption.

In approaches to make optimal N use measurable and monitorable, multiple agri-environmental N indicators have been adopted and implemented as regulatory approaches, including in German legislation (StoffBilV 2017; DüV 2017, 2020). However, the economic boundaries for agricultural activities and societal preferences regarding sustainability and climate protection both undergo constant change over time. As a result, policymakers continually need to meet different objectives and to develop practicable and justifiable targets which can pass through the legislative process and thereafter.

A legal framework at European Union (EU) level concerning N application was established in 1991 and has since been implemented by EU member states (EU-MS). The Nitrates Directive (91/676/EEC) is a key part of EU agri-environmental policy and sets thresholds for nitrate concentrations in groundwater and surface water bodies, to combat serious environmental issues and avoid additional contamination (European Council 1991). Since then, EU-MS have adopted national laws and regulations, e.g., in Germany an ordinance regulating N fertilizer application came into force in 1996 (Fertilizer Application Ordinance, DüV).

Since then, N policy in Germany has gone through multiple developments, with major changes. Regulations on N fertilizer application developed over time (DüV 1996, 2007, 2017, 2020) and led to implementation of soil surface N budgets and balanced fertilization planning as agri-environmental indicators in German legislation. Additionally, an ordinance on sustainable and resource-efficient N utilization (Ordinance on Substance Flow Analysis, StoffBilV) was enacted in 2017, resulting in a further N indicator, gross farm-gate balance, being embedded in regulations limiting excess N inputs. This regulatory approach, which serves to secure compliance with the German Fertilizer Law, is not based on EU legislation but is directed towards achieving the goals in the Climate Action Program 2030 and the German Sustainable Development Strategy (DüngG 2021). Both are national frameworks defining the target of reducing the surplus in the German sectoral N balance from around 87 kg N/ha (in 2018) to 70 kg N/ha in 2030, based on a consecutive five-year average deriving from 117 kg N/ha in 1992 (German Federal Government 2019, 2021a). This political development created the basis and prompted the need for research on the questions addressed in this thesis, which focused on the design, integrity, and *status quo* levels of past and future regulatory approaches and respective N indicators for limiting excess N use. Reliable, robust, and informative agri-environmental indicators based on consistent data requirements are needed to assess N utilization in farming systems, identify potential for improvement, support policymakers in decision-making, and improve acceptance among farmers and relevant authorities.

1.2 Research questions

In the present thesis, the aim is to evaluate current N indicators used in German legislation and their relevance for implementation of policy measures, to assess the current N use efficiency (NUE) level of the agricultural sector in Germany, and to examine potential for improvements.

The research questions addressed were as follows:

a. Regulatory approaches for on-farm N management

- What regulatory approaches and associated agri-environmental N indicators are currently used in German nutrient policy?
- How do these regulatory approaches differ:
  - in design and purpose?
  - with regard to data reliability and data uncertainty?
  - in terms of limits for maximum N fertilizer inputs?
- Do these limits for N fertilizer inputs vary according to farm type?
- What policy recommendations can be derived to improve the regulatory approaches?

b. NUE on farm level

- What is the current NUE level in the German agricultural sector and its farm types?
- How does NUE differ between farm types?
- How does NUE differ within farm types?
- Which regional, farm structural, and socio-economic determinants are linked to N performance?
- What policy recommendations can be derived to improve NUE?

1.3 Objectives

Based on the above research questions, the overall objective of the thesis was to assess the functionality of regulatory approaches addressing N utilization embedded in German legislation, aiming at providing a basis for improving existing N indicators and deriving new N indicators in order to optimize N management.

Specific objectives of the work were to: (i) compare and identify robust N indicators embedded in national regulations with regard to data reliability and data uncertainty; (ii) outline further measures for improving indicators; (iii) develop a methodological approach for calculating relevant N flows in complex agricultural systems of different types and thus to estimate several N indicators based on farm accounting data; (iv) assess the potential for reducing N emissions through policy measures on

N utilization *ex ante* and *ex post*; (iv) identify links between regional, farm structural, and socio-economic characteristics and N performance on farm level, and (v) develop a plausibility checking approach for deriving reliable efficiency potential values on different system levels for complex farm systems. These objectives were pursued using different data sources comprising selected farm-level data, sub-sectoral data (farm types according to Federal Ministry of Food and Agriculture (BMEL) typology) and sectoral data. The context for the objectives was the changing regulatory framework in Germany brought about by the national ordinances, StoffBilV (2017) for regulating farm-gate balancing and being enacted in 2017, as well as DüV (2017, 2020) for regulating soil surface balancing and fertilization planning and being amended in 2017 and 2020, in order to contribute for achieving the country's ambitious environmental, climate, and sustainability goals.

In the synopsis of this thesis, the findings in Papers I-III are summarized and the importance of robust N indicators in legislation for farmers, control authorities, and (inter-)national reporting is pointed out. Scope for improving the robustness of regulatory approaches and options for different assessment systems (Dt.: "*Bewertungssysteme*") are considered and determining factors in good N performance are proposed. The findings are used to make recommendations on future policy activities addressing N management to assist in transformation towards a sustainable agri-food system.

1.4 Thesis outline

The thesis contains seven chapters. This introductory chapter (Chapter 1) highlighted the overall problem and the motivation for the research, and listed the research questions and specific objectives of the work. Chapter 2 provides a theoretical background and introduces topics relevant when investigating the N indicators embedded in German legislation. Chapter 3 provides a comparative description of regulatory approaches and their respective N indicators with regard to design, data reliability and data uncertainty, and N reduction requirements according to legally defined thresholds (Paper I). Chapter 4 describes sectoral levels for two N indicators, N balance and NUE, and discusses the interrelations between regional, farm structural, and socio-economic characteristics and on-farm N performance (Paper II). Chapter 5 describes robust N indicators on different system scales for dairy farms with different grazing intensities in Northwestern Germany (Paper III). Chapter 6 provides an overall discussion and implications for policy advice, as a synopsis of all research outcomes integrated in this thesis. Lastly, Chapter 7 presents some conclusions based on the findings and analyses. Papers I-III all investigated agri-environmental N indicators and the chapters are arranged according to the logical sequencing of the work performed. However, the issues covered were intertwined, so there are many crossings and partial overlaps. Table 1 shows the key aspects studied in Papers I-III.

Table 1: Key indicators investigated in Papers I, II, and III in this thesis.

Paper	**Farm-gate balance**	**Soil surface balance**	**Fertilization planning**	**Nitrogen use efficiency**
[I]	X	X	X	
[II]	X			X
[III]	X	X		X

2 Conceptual framework

In this chapter, fundamentals of natural science are first presented in order to understand the problems related to N (section 2.1). Due to complex chemical and physical interactions, the N problem can be broken down into several sub-problems that have different negative ecological effects. In order to quantify these, a general overview of agri-environmental N indicators is provided (section 2.2), along with selected N indicators assessed later in the thesis in terms of their design and integrity (section 2.3). Changes over time through which different N indicators have found their way into German legislation are described, using the recently enacted StoffBilV 2017 as a detailed example (section 2.4).

2.1 Role of nitrogen in agriculture and environmental interactions

Nitrogen is a plant macronutrient and as such essential for sustainable and cost-effective crop production. Nitrogen fertilization also plays a key role in agriculture by contributing to higher yields, quality standards, and maintaining soil fertility. Apart from being essential for plant growth, N is also an essential element in protein compounds in food and in feed for livestock, so the level of N fertilization affects human and animal nutrition. This makes N a substantial input for agricultural production in farm systems, including those in Germany. The main N input sources are N fertilizers (mineral and organic), feedstuffs and fodder (domestic and imported), and biological N fixation (Bach et al. 2020; Löw et al. 2021; UBA 2022d). However, imbalances in N supply and uptake leading to N surpluses can occur. On field level, excessive N supply above plant requirements lead to negative externalities, particularly N emissions (Osterburg & Runge 2007).

As N can be very reactive, (an-)oxic chemical reactions lead to transfer of N to the environment (air, soil and water). Nitrogen is distributed in the environment by physical diffusion processes, causing environmental impacts to occur far away from the emission event at times. Farm structural and regional characteristics may also favor the appearance of N emissions in hotspot regions. Thus, the spatial distribution of N emissions in Germany varies greatly, largely depending on farm structural and pedo-climate characteristics (Amelung et al. 2018; Häußermann et al. 2020b; Schulte-Uebbing et al. 2022; Zinnbauer et al. 2023). The open N cycle in agriculture (Rockström et al. 2009; Steffen et al. 2015), primarily associated with the manufacturing of mineral fertilizer in the Haber-Bosch process, causes environmental problems, as excessive N utilization in agricultural production systems and the high reactivity of N lead to negative effects on soil, air, water, biodiversity, human health, and global climate (Sutton et al. 2011; Erisman et al. 2015; Erisman 2021; van Damme et al. 2021).

The agricultural sector in Germany plays a central role in the current national N cycle, as N fluxes into and out of the sector contribute the largest amount of reactive N to the environment. The agriculture sector is responsible for 67% of total N emissions, followed by industry and energy (16%), transport (11%), and households, waste, and wastewater (6%). The majority of total N emissions in Germany, around 1,550 kt/year as a mean value between 2010 and 2014, is emitted into the air as ammonia (NH_3), followed by nitrate (NO_3) discharge into surface waters, oxidized N (NO_x) emissions and nitrous oxide (NO_2) released into the atmosphere (Bach et al. 2020; Geupel et al. 2021).

Consequently, any discussion about achieving sustainability goals must include the N problem, as N affects the quality of aquatic and terrestrial ecosystems and human health, and contributes to global warming (Sutton et al. 2011; Erisman et al. 2015; Erisman 2021; van Damme et al. 2021). Nitrogen-related sustainability goals are explicitly addressed in the German Sustainable Development Strategy through “2.1.a Nitrogen surplus in agriculture”, “3.2.a Emissions of air pollution”, “6.1.b Nitrate in groundwater”, “13.1.a Greenhouse gas emissions”, “14.1.a Nitrogen inputs via the inflows into the North and Baltic Seas”, and “15.2 Eutrophication of ecosystems” (German Federal Government 2021a). Additional goals relate to human N utilization (Geupel et al. 2021). In the following, the most important natural relationships are presented, since knowledge of the complexity of the N cycle and resulting problems from its utilization is essential for its contextualization.

Effects on soil and water

Nitrogen can exist in the soil in different physical forms. As ammonium (NH_4), it is initially bound to soil particles, but over time it is converted into nitrate by soil microorganisms. Nitrate is highly mobile in the soil and can be displaced to groundwater with the leachate, especially in autumn after harvest and with heavy precipitation (UBA 2021). The risk of leaching is highly management-dependent (e.g., fertilizer management, tillage, crop rotation) and site-specific (e.g., soil type – such as evaporation or depth to groundwater – slope, historical land use) (Barunke 2002; Osterburg & Runge 2007; Amelung et al. 2018). In groundwater – and subsequently in drinking water –– nitrate can be converted under certain conditions into nitrite, which poses a health risk, especially for infants (Geupel et al. 2009; SRU 2015).

Excessive N fertilizer application can also contribute to soil acidification, in particular with acid fertilizers such as ammonium sulfate. If nitrate is not taken up by vegetation but leached, soil acidification accelerates due to base leaching, which is associated with simultaneous changes in the soil structure and living conditions for soil (micro-)organisms. This can have an impact on soil fertility, ultimately resulting in lower yields and lower quality of plant products (SRU 2015; UBA 2021). Although the availability of micronutrients may increase in an acidic environment, increasing pH stimulates microbial activity, resulting in the degradation of humic matter and the release of N (Amelung et al. 2018).

Since groundwater is also connected to surface waters, nitrate may be carried into rivers, lakes, and seas. The agricultural contribution to nitrate pollution is around 77% (Bach et al. 2020). Surface waters are also enriched with N through ammonia deposition from air and erosion processes. The increased supply of N causes an increase in algae production and a shift in algae species diversity. This in turn leads to oxygen deficiency in sediment and deeper water, harming fish populations and ground fauna (Geupel et al. 2009; SRU 2015; Geupel et al. 2021; UBA 2021).

It is not only aquatic ecosystems that are affected, since negative effects can be observed in terrestrial ecosystems beyond the agricultural land itself. The cause is primarily transport of gaseous N emissions in the air flow, in particular ammonia and NO_x released into the air in gaseous form and then undergoing complex chemical reactions. In particular, farm structural characteristics influence the level of ammonia emissions (e.g., high pH, low soil moisture content, high temperatures) rather than natural conditions (SRU 2015; Amelung et al. 2018; UBA 2021). Atmospheric N deposition is strongly linked to anthropogenic actions and amounts to about 20 kg N/ha/year on average, with maximum values of up to 80 kg N/ha/year (UBA 2022b). The temporal and spatial distribution is difficult to identify, since the transport is long-range. The agricultural contribution to ammonia emissions is around 95% (Bach et al. 2020). Deposition of gaseous N emissions on oligotrophic sites can lead to changes in biodiversity in favor of nitrophilous plants, and to the extinction of N-sensitive species (Erisman 2021; van Damme et al. 2021). Biodiversity is particularly threatened in semi-natural ecosystems (e.g., heathland, moor, forest). High ammonia concentrations, e.g., in the immediate surrounding of animal houses, are also harmful to plants and to human health (SRU 2015; Erisman 2021; Peng et al. 2022).

Effects on air

Nitrous oxide is a climate-relevant gas and comprises around 5% of climate-relevant gases (UBA 2022a). Agricultural activities are responsible for around 80% of nitrous oxide emissions in

Germany (Bach et al. 2020). Increasing emissions of climate-relevant gases intensify the natural greenhouse effect. In addition to an increase in the average temperature on Earth (between 2.1 and 3.4 degrees Celsius according to actual National Determined Contributions), anthropogenic climate change is associated with a poleward shift in vegetation zones, a change in regional intensity of precipitation, and increased frequency of extreme weather events (IPCC 2022). Nitrous oxide and nitrogen monoxide (NO) are formed during denitrification processes in the soil and then released as atmospheric N, which is influenced by pedo-climate characteristics (e.g., presence of biodegradable organic matter, high soil moisture and temperature, absence of oxygen). In addition, nitrous oxide volatilizes during application and storage of mineral and organic fertilizers (Geupel et al. 2009; SRU 2015).

Nitrous oxide is photolytically converted into radicals in the stratosphere. These radicals contribute to the degradation of stratospheric ozone, leading to an increase in ultraviolet radiation at the Earth's surface. This can cause negative health effects in humans (e.g., skin cancer, weakening of the immune system), damage to phytoplankton, and cell damage and mutations in higher plants (Geupel et al. 2009; SRU 2015).

2.2 Nitrogen-related agri-environmental indicators

Since there are multiple interactions between polluting substances and environmental media, indicators are often used to make the situation more comprehensible and quantifiable. This section outlines the characteristics of agri-environmental indicators and frameworks, and assesses the importance of indicators and the different approaches to systematization and evaluation in the field of agri-environmental policy. This provides a better understanding of indicator selection in this thesis and the general research field. However, the frameworks do not serve as the theoretical basis for addressing the respective research questions.

Indicators

An “indicator” is a comparatively easy to measure, meaningful key figure that is defined in order to describe a situation that is not directly measurable and often complex. According to OECD (1993), an indicator can be a “parameter or a value derived from parameters, which points to/provides information about/describes the state of a phenomenon/environment/area with a significance extending beyond that directly associated with a parameter value”. Analytically sound and reliable indicators play an important role in the development of political solutions, as this process is generally informed by scientific findings (European Commission 2006; EUNEP 2015). At the intersection of agricultural activities and environmental protection, agri-environmental indicators are used as key figures to estimate and evaluate the environmental impacts of agricultural production systems at farm or regional level (Nieberg & Isermeyer 1994). Their function is to simplify, quantify, and communicate information from agroecosystems (EEA 1999; Meyer-Aurich 2002). Agri-environmental indicators are generally used for the following purposes: (a) national and international reporting, (b) as an impact factor in agri-environmental measures, and (c) as mostly voluntary on-farm agri-environmental information systems (Isermeyer & Nieberg 2003). In the field of policy-making, they identify and supply information on environmental problems, support policy development and priority setting, and monitor and assess effects of policy responses (EEA 1999; European Commission 2006).

Frameworks

For better systematization and comparability of agri-environmental indicators, causal frameworks explaining how society and the environment interact were developed in the 1990s. Based on the Pressure-State-Response ("PSR") scheme (OECD 1993), the enhanced "DPSIR" framework published by the European Environmental Agency (EEA) in 1999 refers to the broader differentiation of "Driving forces", "Pressures", "State", "Impact", and "Responses" (Smeets & Weterings 1999). The framework offers a structure within which to convey the required indicators to enable policymakers to obtain feedback on environmental quality and the effects of past and upcoming political decisions (FAO 2022). The EEA has widely adopted the DPSIR framework, as have national agencies, particularly as an integrated approach for reporting and to provide a comprehensive causal analytical description of relevant processes (Kristensen 2004; BAFU 2015; BfN 2022). Additionally, the DPSIR framework pre-supposes a series of causal relationships between driving forces (economic sectors, human activities) through pressures (emissions, waste) to states (physical, chemical, and biological) and impacts on ecosystems, human health, and functions, ultimately leading to political responses (prioritization, target setting, indicators) (Kristensen 2004).

While the DPSIR framework contributes to systematization with a high degree of acceptance, it lacks selection recommendations for indicators (Barunke 2002). Therefore the IRENA (Indicator Reporting on the Integration of Environmental Concerns into Agriculture Policy) framework was developed in 2005 on EU level by COM and EEA, based on the maxim to consider economic, environmental, and social effects of policies in decision-making (European Commission 2001). The goal was to develop a suitable set of agri-environmental indicators in order to integrate sustainable development criteria and impacts into policy decisions, and to ensure coherence between all EU policies. Several policy purposes were identified (European Commission 2006): (i) to provide information on the *status quo* and ongoing changes, (ii) to monitor how agriculture affects the environment, (iii) to make impact assessments of agri-environmental policies on farmers' environmental management, (iv) to inform agri-environmental policy decisions, and (v) to explain agri-environmental links to the wider public. Since then, the IRENA approach has led to the identification of a set of key indicators, their main data sources, the time series used, and generally accepted definitions. Nitrogen-related examples of agri-environmental indicators in IRENA are "mineral fertilizer consumption", "gross nitrogen balance", "atmospheric emissions of ammonia", and "nitrates in water" (EEA 2005). However, limitations still exist, e.g., regarding harmonized definitions and data quality, or methodological and conceptual inaccuracies. A comprehensive list of the IRENA indicators and their explanation and classification according to the DPSIR framework has been formalized (EEA 2005). In Germany, the German Federal Statistical Office has published an indicator report every two years since 2006 (DESTATIS 2021). In the latest German Sustainable Development Strategy, a set of 75 key indicators is established, addressing in the N context e.g., "agricultural N surplus" and "nitrates in groundwater", (German Federal Government 2021a), both of which are considered pressure indicators (Oenema et al. 2003; Svarstad et al. 2008; Klages et al. 2020a). For instance, an increase in food demand (Driving force) may result in intensifying agricultural activities through greater N fertilizer inputs, which increases nitrate runoff into neighboring surface waters (Pressure). This in turn causes eutrophication of downstream water bodies (State) that affects aquatic life and biodiversity (Impact). Nitrogen fertilizer taxes, ambitious N balance thresholds, non-tradable fertilizer certificates, and promoting organic farming are among the potential ways to deal with this issue (Response) in order to prevent nitrate leaching.

An earlier framework by Scheele et al. (1993) defines elements of an environmental policy strategy to solve the N problem in agriculture. This provides a basis for systematization and assessment in environmental policy instruments, and for the indicators studied in this thesis. The environmental concept in that framework has three main pillars, categorized as:

1. Environmental quality targets: drinking water protection, protection of surface waters, preventive water protection, wildlife and landscape conservation, climate protection, protection of the ozone layer.

2. Action parameters on environmental policy: technological approach (e.g., emissions, immissions, N surplus, product), addressee (e.g., farmer, consumer), regulatory space/scope of application (e.g., national, EU-MS, global level), instrument (e.g., levy, tax, subsidy).
3. Assessment criteria: opportunity costs (waiving of alternative production, achievement of social-political goals), administration and control costs, consensus building costs.

Focusing on the action parameters of environmental policy, the framework in the present thesis was specified as follows: The main subjects of the analysis were N indicators, N balances on different system scales, and fertilization planning (*technological approaches*), which are regulated nationally and on farm level (*scope of application*) in respective ordinances focusing on N application (DüV 2017, 2020) and resource-efficient use of N (StoffBilV 2017) (*instruments*), addressing agricultural farms (*addressee*). These technological approaches embedded in national regulations are referred to hereafter as “regulatory approaches”. The environmental quality targets considered were those established e.g., by the German Sustainable Development Strategy or the Climate Action Program 2030 (German Federal Government 2019, 2021a). The assessment criteria used as part of the analysis are defined and analyzed in Chapter 3.

Several publications categorize environmental policy measures differently, e.g., as hard (e.g., regulatory, fiscal, economic, voluntary agreement) and soft (information and education, research) instruments (UNFCCC 2022), or as regulatory (e.g., commandment, ban), economic (e.g., subsidy, tax), or informative (e.g., labelling) instruments (Michaelis 1996). However, the regulatory approaches and associated N indicators analyzed in this thesis can be predominantly assigned to the regulatory category. They are described in more detail in section 2.3, as is a further N indicator related to efficiency which can easily be derived from these regulatory approaches.

2.3 Nitrogen indicators investigated

Three well-established agri-environmental N indicators as entry points for regulations on excess N fertilizer inputs were investigated in the present thesis. Their design and different variations, usage, and informative value are explained in this section.

2.3.1 Nutrient balance

A nutrient balance quantifies and contrasts the inputs and outputs of an agricultural system. Nutrient balances can be distinguished according to the system boundaries set with regard to spatial scale (e.g., nation, region, farm), system (e.g., farm-gate, soil surface) or time scale (e.g., month, year), the nutrients included (e.g., phosphorus (P), N), and the designated use (input – *Aktiva* – or output – *Passiva* – parameters). A further distinction can be made as to whether N emissions from volatilization are excluded (net) or included (gross). The deficit or surplus is part of the nutrient balance and represents a sum parameter. Usually it is set in relation to the utilized agricultural area (UAA), more rarely in relation to livestock units (LSU). It is a relevant indicator for assessing nutrient management on different levels (e.g., field, stable, farm) and potentially resulting environmental pollution caused by N emissions as described in section 2.1, whereas the cause-effect chain can vary greatly in space and time (Oenema et al. 2003; Bach & Frede 2005; Bahrs & Gamer 2015; SRU 2015). Calculating N balances and showing the deficit or surplus can help increase awareness of problems associated with N imbalances, improve understanding of the N cycle and the relationship of nutrient inputs and outputs, and guide improvements in N management. It also serves as a regulatory policy approach (Oenema et al. 2003; Nevens et al. 2006). The term "N budget" (United Nations 2014) differs slightly in definition from "N balance", as the budgeting approach depicts both marketable products *and* N losses from the system as N outputs. Nevertheless the terms balance and budget are often used synonymously in the literature (Häußermann et al. 2020b; Klages et al. 2020b). In the following, the gross farm-gate balance and the net soil surface balance are described in more detail, as these are the most commonly used and most widely implemented in German legislation.

Farm-gate balance

For decades, studies defined the gross farm-gate N balance as an appropriate approach for budgeting N flows of agricultural activities. Particularly in German linguistic usage, there are many different terms that describe the concept of gross farm-gate balancing or have many similar elements, e.g., the direct translation "*Hoftorbilanz*" (Bach et al. 1997; VDLUFA 2007), but also "*Stoffstrombilanz*" (Steurer 1994; Klages et al. 2017), "*Nationale Grundmineralbilanz*" (Bach et al. 1997), "*Betriebliche Gesamtbilanz*" (VDLUFA 2007), and "*Import/Export-Bilanz*" (Vereinte Nationen & BAFU 2014). As marketable N exports and imports are considered (plant- and animal-based), N accounting is generally based on invoices or delivery notes (VDLUFA 2007), and N amounts are derived from product declarations (e.g., mineral fertilizers) or standard values (e.g., N content in animals and animal products) (StoffBilV 2017; Amon et al. 2021; Klages & Schultheiß 2022). Biological N fixation (BNF) and atmospheric deposition (ATD) are usually also considered as N imports, while gaseous losses are included and not deducted from respective parameters in a gross calculation. As a result, the N surplus or deficit indicates the potential N pressure on the environment, whereas the environmental medium affected is not addressed. Division into N storage in soil and N loss paths (gaseous, leaching, surface washout) is not possible.

Soil surface balance

A net soil surface N balance considers the N input and output flows on field level. Thus, mineral and organic fertilizers and BNF are accounted for as N inputs, whereas harvested crops and harvested or grazed roughage and removed crop residues belong to N outputs. As these are mainly internal N flows, standard values (e.g., animal category-based excretion factors) or individual estimates (e.g., N concentration in roughages) are used for estimation. As this is a net calculation, manure- and digestate-specific gaseous N losses for volatilization in housing and storage, during field application, and on pasture are deducted beforehand, and not considered in budgeting. Generally, maximum standard excretion factors depending on animal species and housing system are provided by legal authorities, but individual figures may be used. The latter is particularly relevant when lower N values are achieved through better manure management technologies (Häußermann et al. 2020a; DüV 2020). These factors offer greater scope for inaccuracies (Myrbeck et al. 2019). Due to the deduction in gaseous N losses, the N surplus includes water pollution with nitrates and can be considered as an “agri-drinking water indicator” (Klages et al. 2020a).

2.3.2 Nitrogen use efficiency

Nitrogen use efficiency (NUE) is a key indicator for assessing the N performance of agricultural systems and sub-systems (Oenema et al. 2003; Quemada et al. 2020). It is calculated as total N outputs over total N inputs, and provides an indication of e.g., kg N incorporated into crop products per kg N input (Vereinte Nationen & BAFU 2014). According to Powell et al. (2010), NUE can be determined on three levels: (a) considering the farm system as a whole (farm-NUE), (b) mineral and organic fertilizer conversion into crops and/or pasture (field-NUE), and (c) feed conversion (feed-NUE), defined as the ratio between N outputs and N inputs within the respective system boundaries set. Thus, the method and the resulting dimensionless efficiency value are easy to understand and simple to interpret (EUNEP 2015). A first approach for assessing NUE on different levels with benchmark values, aiming to define optimum efficiency values while avoiding soil mining or a high risk of N losses, has been developed (EUNEP 2015), by a consortium of experts from science and the food and fertilizer industry. Further refinement of that approach is ongoing (Wuepper et al. 2020; Winiwarter et al. 2022; Zhang et al. 2022).

2.3.3 Fertilization planning

Since every crop has its individual N requirements, it is essential to determine the optimum fertilizer rate on plot level before the vegetation period starts, for economically and environmentally responsible plant production. Fertilization planning of this type is well-established in the farming community. Most EU-MS are now using fertilization planning for advisory purposes and more frequently also for regulation purposes, but the design and application of plans vary (Klages et al. 2020b). In most approaches, fertilization planning is a site-specific tool based on crop-specific N demand, considering regional- and management-specific N supply. In Germany, the crop-specific N demand values are defined in national legislation, whereas the calculated crop- and farm-specific N demand can differ from the standard value depending on individual yield potential in the preceding five-year period. Additionally, deductions or additions are made to account for residual N from soil reserves, leguminous N fixation, manure applied in the previous year, and/or catch and cover crops (DüV 2020; Klages & Schultheiß 2022). In Germany, the results of the crop- and site-specific fertilization plans are used to make recommendations on N fertilization, where the cumulated N recommendations for a farm can be seen as an upper limit for N fertilization that must be respected on average over the UAA. Accordingly, individual adjustments and N excesses or deficits on single plots are still possible.

Above all, it should also be noted that slightly different methodologies are used by different countries and organizations to determine the N indicators employed. Accurate and consistent documentation of the N parameters involved in calculating indicators is therefore crucial to enable comparison between years, and to compare observed values with reference or benchmark values (Bach et al. 1997; EUNEP 2015; OECD 2019). Accordingly, this should be considered when setting indicative target values, as challenges may arise in terms of national and international comparability (Leip et al. 2015). With regard to the DPSIR framework presented in section 2.2 of this thesis, the N indicators used can be considered “pressure” indicators, as they describe N pressure on environmental media.

2.4 Recent developments in German nitrogen policy

Since the first expert report on environmental problems of agriculture in 1985, many environmental issues related to agricultural activities have been clearly addressed and explicit recommendations to policymakers have been formulated (SRU 1985). In 1991, the Nitrates Directive (91/676/EEC) became part of EU agri-environmental policy in response to the serious environmental problems caused by excessive release of reactive N and to prevent further contamination (European Council 1991). Individual EU-MS had the choice of either implementing the Nitrates Directive through a so-called action plan only for designated polluted areas, or for the entire national territory. In both cases, monitoring of the success of measures introduced in the action plans was required, in a four-year-rotation (Kuhnt 2017). Since then, nutrient policy in Germany has undergone further changes.

The DüV, which came into force in January 1996 (DüV 1996), is the fundamental element of the German action program and implements the Nitrates Directive into national law. The regulatory approaches embedded in the original legislation involved fertilization planning *(ex ante: determination of the nutrient demand of crops, nutrient supply by soil, and resulting amount of fertilizer needed)* and nutrient balancing *(ex post: calculation of nutrient input by fertilizers and other sources, and nutrient output by yield of the crop in question)* for N, P, and potassium (K). For nutrient balancing, the farmer had a choice between two types of balances (*soil surface* or *farm-gate*) with different system boundaries and system scales. Both types of balance involved only mandatory recording, and neither had an assessment system with a corresponding threshold value.

In March 2007, a revised version of the ordinance was enacted whereby the approaches for regulating N management were modified (DüV 2007). Fertilization planning and nutrient balancing (for N and P) were still basic approaches in the modified DüV, but for nutrient balancing the type of balance (soil surface balance) and an assessment system became mandatory. The legislation allowed a choice between a soil surface balance and an aggregated plot level balance (soil surface balance for every plot, aggregated afterwards). The threshold value for N varied depending on the reference period, from 90 kg N/ha (mean value for the period 2006-2008) to 60 kg N/ha (mean value for the period 2009-2011 and thereafter). For fertilization planning, specifications were defined in an Annex to the ordinance, for example default values for deductions according to plant-available N supply from catch crops and residues.

In 2012, the European Commission (COM) has already demanded changes to the DüV 2007. Therefore, Germany was charged with infringement in 2013 and an action brought by the COM came before the European Court of Justice in 2016 (Salomon et al. 2016; Kuhnt 2017). The main points of contention were the permitted degree of nitrate pollution and required measures (in particular the excess threshold value of 60 kg N/ha), the length of retention periods, the capacity of tanks for manure storage, and fertilizer application on steeply sloping or waterlogged, snow-covered, or frozen surfaces (Kuhnt 2017).

Contemporaneously, from May 2011 onwards until November 2012, 34 experts from science and administration were collaborating for evaluating the DüV 2007. A final report with options for improving DüV was published, focusing on measures to ensure targeted and needs-based fertilization, mitigate environmental risks related to fertilization, and effective control authorities. Thus, the results provided comprehensive and concrete measures to increase effectiveness in terms of fertilization planning, the length of retention periods, capacity of tanks for manure storage, manure application techniques, methodology and assessment of soil surface nutrient budgets, and others beyond (Osterburg & Techen 2012).

As a consequence, DüV was again amended and a new version came into force in May 2017 (DüV 2017). In addition to a wide range of modifications and new restriction, e.g., regarding manure application on arable land in autumn after harvest, extending the upper application limit of 170 kg/ha organic N from manure to organic N from compost and digestate, and increasing on-farm manure storage capacity, there were also changes in regulatory approaches. Concerning fertilization planning, specifications were introduced e.g., for deductions due to residual N from the soil reserves, leguminous N fixation, or deviating yield levels for crops and grassland. These modifications made fertilization planning more complex and precise, and also potentially more restrictive regarding the N application limit. For nutrient balancing, the maximum N surplus was reduced from 60 to 50 kg N/ha.

Following a revision of the German Fertilizer Law, in January 2018 a further ordinance to ensure sustainable and resource-efficient use of nutrients on farms was included in German legislation. With this Ordinance on Substance Flow Analysis (StoffBilV 2017), nutrient balancing for N and P at farm-gate level was (again) part of regulations to fulfil national goals, and became mandatory for several farm types at the first time. A detailed description of the addressees and development of StoffBilV is provided in the following section.

In a judgement of the European Court of Justice on 21 June 2018, Germany was found guilty of all charges regarding inadequate implementation of the Nitrates Directive based on the German legislation in 2013 (European Court of Justice 2018). Despite the amendment of DüV in 2017, further adjustments to German fertilization legislation were required by COM in order to avoid a second court proceeding and a potential penalty, with daily fines of around 850,000 € and a one-time fine of around 12 million € (Agra-Europe 2019).

As a consequence of this judgement, DüV was again amended in April 2020 (DüV 2020). Fertilization planning was modified regarding the maximum exceedance of the calculated N requirements due to subsequent circumstances (a maximum of 10% was set) and a higher minimum effectiveness for use of N in manure and digestate. Recording and assessing soil surface balance, or aggregated plot-level balance, had to be abolished (Latacz-Lohmann et al. 2021), because the European Court of Justice did not accept the N balance surplus above zero permitted by DüV 2017. Since then, fertilization planning is the key regulatory approach for determining N application limits in Germany, as in most EU-MS (Klages et al. 2020b).

Within the national General Administrative Regulation on Designation of Nitrate-Polluted and Eutrophic areas, a further legal text was established in November 2020. It governs the methodological framework for designating areas polluted by nitrates or phosphate (Latacz-Lohmann et al. 2021). However, due to further pressure from COM, this regulation had to be amended in August 2022 to include more restrictive requirements, e.g., on manure management and fertilizer application in nutrient-polluted and eutrophic areas (AVV GeA 2022). In 2024, another ordinance will be implemented on monitoring compliance with DüV (Dt.: "*Nitratmonitoring*"), in particular a requirement for continuous evaluation of the measures in DüV and reporting to COM (BMEL 2020a, 2022b). As a result of these changes to German legislation, at the beginning of 2023 the legal proceedings brought by COM were suspended, but not cancelled.

Federal enactment, evaluation and amendment of StoffBilV

The German Ordinance on Substance Flow Analysis regulates the method of preparing, reporting, and assessing farm-gate balances in Germany being enforced on January 1st, 2018 (StoffBilV 2017). It is a regulation implementing national law on defining 'good practice' requirements for nutrient utilization to ensure sustainable and resource-efficient use of nutrients on farms. Hence, StoffBilV reporting is not part of EU Cross-Compliance, as it is not based on EU legislation. It also pursues the national goal of 70 kg N/ha surplus in the agricultural sector defined in the Climate Action Program 2030 and the German Sustainable Development Strategy (German Federal Government 2019, 2021a). At the time of enactment, German Fertilizer Law stipulated that from 1 January 2023 onwards, addressees would include all farms with more than 20 ha or with more than 50 LSU (DüngG 2021; DLG 2023), as underpinned in the Climate Action Program 2030 (German Federal Government 2019). Until then, the only addresses were (i) farms with more than 50 LSU or more than 30 ha UAA, with a livestock density of more than 2.5 LSU/ha, (ii) farms with animal husbandry importing organic fertilizers, and (iii) farms managing a biogas plant and functionally linked to a farm with animal husbandry according to (i) or (ii) and using internal or external organic fertilizers (StoffBilV 2017). The legally defined extension from 2023 covers a total of more than 93% of UAA, more than 93% of LSU, and more than 56% of all farms in Germany (Löw et al. 2021). The BMEL was mandated by the German Bundestag with completing an evaluation process by the end of 2021, addressing previously defined key questions (German Federal Government 2019), in order to analyze the effectiveness and identify potential for improvements, e.g., regarding the design, cost reductions, and assessment of N and P farm-gate balances. The resulting report was intended to provide the basis for an amendment scheduled for January 2023. However, the amendment has been postponed and has not yet come into force.

The process from developing and enforcing StoffBilV 2017 until its intended amendment in 2023 was carried out by scientific, administrative, and consultancy experts, overseen by BMEL and Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). The process was divided into three major steps:

1. *Development and definition of methodological principles for farm-gate balancing and options for assessing N surpluses* (2016-2017). From 2016 to 2017, 49 experts from scientific institutions (federal research institutes, universities and technical colleges), administrations (federal and state (*Länder*) level), and the private sector (consultancy, associations), subdivided into several working groups, collaborated in order to define a methodological framework for the farm-gate balance as an regulatory approach, as well as options for assessing the surplus and setting threshold limits. The results were published in a report (Klages et al. 2017).
2. *Evaluation of the methodological approach and the assessment system for N implemented in StoffBilV* (2019-2021). StoffBilV was enacted in 2017 and came into force in 2018. From 2019 to 2021, 31 experts from scientific institutions, administrations, and the private sector cooperated, subdivided into two working groups (group I and II). Group I discussed the results of a survey with technical departments of the Länder and consultancies, sharing experiences and devising options for improvements of StoffBilV. In group II, options and

criteria for an advanced assessment system for N surpluses and for a novel assessment system for P surpluses were developed. The results were published in a report (Löw et al. 2021).

3. *Amendment, cost calculation, and enactment of StoffBilV* (2022-2023 (expected)). In 2022, policy advisors from BMEL began to compile an amended version of StoffBilV 2017, considering findings documented in the evaluation report. Scientists from the federal research center Thünen Institute were involved in this process in order to respond to specific questions, explain complex context linkages, and point out critical issues. They also advised on the cost analysis to be finalized in 2023 for the National Regulatory Control Council (Dt.: "*Normenkontrollrat*"), an independent committee of the German Government which assesses the costs associated with new or amended legislation. The results of the StoffBilV cost analysis will be published together with the amended draft version to the Bundesrat in a report (Dt.: "*Bundesrat Drucksache*") for *Länder* voting. The schedule of the German federal administration anticipates a revision of DüngG (2021) and amendment of StoffBilV in 2023 (BMEL 2022d).

3 Comparison of regulatory approaches for determining application limits for nitrogen fertilizer use in Germany (Paper I)

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Comparison of regulatory approaches for determining application limits for nitrogen fertilizer use in Germany

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Abstract

This study examined the suitability of three different indicators as entry points for agricultural regulation for limiting excess nitrogen (N) fertilizer inputs in Germany: net soil surface balance, gross farm-gate balance, and fertilization planning. Data on about 6000 farms in Germany were grouped into types for comparative analysis. The design of the regulatory approaches and the reliability of constituent parameters were then examined, and proportions of affected farms and mean N reduction requirements were identified. This revealed that: (a) design and purpose of the regulatory approaches differ, but the data requirements are very similar; (b) the parameters involved differ in reliability and integrity; and (c) the limits for maximum N fertilizer input at farm level vary with approach and farm type.

List of abbreviations

BMEL	Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture)
BNF	biological nitrogen fixation
COM	European Commission
DüV	Düngeverordnung (Fertilizer Application Ordinance)
EU	European Union
FADN	farm accountancy data network
FarmB	farm-gate balance
FertP	fertilization planning
MINAS	mineral accounting system
N	nitrogen
NIRS	near-infrared spectroscopy
NUE	nitrogen use efficiency
SoilB	soil surface balance
StoffBilV	Stoffstrombilanzverordnung (Ordinance on Substance Flow Analysis)

1. Introduction

1.1. Background

Crop targeted and balanced N fertilization is necessary for optimal plant nutrition and at the same time to reduce environmental impacts. Loss of reactive N compounds from farms is a major ecological challenge, these compounds threaten biodiversity, climate, and human health (Sutton and Bleeker 2013). The EU Nitrates Directive (91/676/EEC) aims to reduce nutrient losses from agricultural activities in order to protect groundwater and surface waters from nitrate emissions (European Commission 1991). In Germany, the Directive is implemented through the Fertilizer Application Ordinance (DüV) (DüV 2020). On the background of the judgement of the European Court of Justice from 21 June 2018 for inadequate implementation of the Nitrates Directive, the DüV was amended in 2020 (Kuhn *et al* 2020). The amended version abolishes the need for nutrient comparison in a nutrient SoilB, and tightens the rules on FertP. For regions exceeding the nitrate threshold value for groundwater of 50 mg NO_3 L^{-1} or above 37.5 mg NO_3 L^{-1} with an increasing trend (e.g. in high livestock regions in Northwestern and Southern Germany, or low precipitation region in East Germany), strict and harmonized measures to reduce water pollution by nitrates must be implemented (Wolters *et al* 2021). Since 2021, the quantity and quality of measuring stations for the classification of nitrate sensitive areas has been increased, and a standardized methodology has been prescribed (BMEL 2020). In order to achieve the German target for sustainable N management embedded in the German Sustainable Development Strategy, the Ordinance for Substance Flow Analysis (StoffBilV 2017), a FarmB framework, was introduced in 2018 (The Federal Government 2020). This study compared the three regulatory approaches (SoilB, FertP, FarmB) as performance indicators for nutrient management in terms of structure, control, and enforcement, and the effects on N management at farm level. The current state of the approaches and their potential, similarities, and differences in agri-environmental policy were also compared.

Nutrient policy in the EU, and especially in Germany, is undergoing major changes (Klages *et al* 2020a), most recently through the abolition of SoilB in German regulations (Klages *et al* 2020b). At member state level, the gross nutrient balance in 2017 was only 62 kg N ha^{-1} per utilized agricultural area (UAA) in Germany, while it was 187 kg N ha^{-1} in the Netherlands (Eurostat 2020a). However, the Netherlands has already implemented fertilization planning as a regulatory approach, according to COM requirements, while in Germany two regulatory approaches (FertP and SoilB) were applied contemporaneously until 2020. Due to the degree of nitrate pollution, lack of improvements in German groundwater bodies, and a dispute about required measures, Germany was challenged with infringement in 2013 (Salomon *et al* 2016) and found guilty in 2018 (European Court of Justice 2018). Around 20% of EU-wide infringement cases in 2019 were within the environment policy area (European Commission 2019b), many relating to the Nitrates Directive, e.g. in Germany, Greece, Belgium, and Austria (European Commission 2019a). This illustrates the enormous bureaucratic effort required to ensure implementation of the Nitrates Directive in EU Member States.

Germany is at a turning point: SoilB has been abolished by the national legislative authority and FertP has been strengthened, as it is considered the preferred approach under the EU Nitrates Directive. However, FarmB is legitimized by the national targets set for sustainability and climate protection, and, thus, by the sovereign of Germany, the Bundestag. The Federal Government has set the goal of 70 kg N ha^{-1} for FarmB of the agricultural sector to meet sustainable standards in the context of water and air quality, biodiversity and climate protection (The Federal Government 2020). This requires a N surplus reduction of about 20 kg N ha^{-1} (DESTATIS 2020). A policy-relevant question addressed in this paper is which performance indicator is best for nutrient management.

FertP, SoilB, and FarmB are approaches of agri-environmental policies whose results are indicators for multiple purposes, e.g. monitoring or control (Klages *et al* 2020a). Fertilization planning and nutrient balancing inherently provide diverging views on the fertilization process: fertilization planning is performed *ex ante* in order to limit N excesses through timely and needs-based application, while nutrient balancing of N inputs and outputs is performed *ex post*. Nutrient balancing provides information about (a) production efficiency, e.g. on field (=UAA) (SoilB) or farm (FarmB) level, (b) environmental pressure (OECD 2013), and (c) links between nutrient use in agriculture, nutrient losses to the environment, and sustainable[1] soil nutrient usage (Eurostat 2017).

1.1.1. Soil surface balance (SoilB)

SoilB, a net soil surface balance related to accountable N inflow of the applied fertilizer, was a legally binding approach for German farmers until 2020. For calculation of SoilB, standard values had to be used, e.g. excretion factors for N and phosphates depending on animal category, development stage, feed composition, and nutrient concentrations in harvested crops. Individual estimates were also accepted, e.g. for nutrient concentrations in roughages in compliance with minimum values. N removal by harvested/grazed roughage crops was estimated considering animal category, development stage, type of husbandry and animal numbers. Substantial losses (15%/25%) could be deduced from the calculated N removal from the field/grassland by roughage. Also, manure- and digestate-specific gaseous N losses were deduced from standard excretion figures for volatilization in housing and storage (15%–45%), during field application (5%–10%), and on pasture (75%), depending on animal species. Since these are maximum factors to be used, lower ones can also be taken due to better application or aeration technology (DüV 2017, 2020, Häußermann *et al* 2020). An additional N input, BNF, was mostly deduced from tables as a function of leguminous species cultivated on arable land or their proportion in grassland (equation (1)). The target for net SoilB was an N surplus $\leqslant$50 kg N ha^{-1} as a 3 year mean (DüV 2017). The N surplus in SoilB was taken as an agri-environmental indicator of potential N emissions and a ‘pressure indicator’ of potential nutrient losses to the environment, i.e. it indicated the potential threat of reactive N compounds to the environment with its different media. Nutrient surpluses can lead to eutrophication and surface and groundwater pollution (Leip *et al* 2015, SRU 2015, Jansson *et al* 2019), while nutrient deficiencies can decrease soil fertility and increase erosion (Eurostat 2020b). Indicators such as field NUE can be deduced from SoilB (Löw *et al* 2020).

$$\mathrm{SoilB}\ \left[\mathrm{kg\,N\,ha}^{-1}\right] = \frac{N_{\mathrm{applied}} - N_{\mathrm{removed}}}{\text{utilized agricultural area}}. \quad (1)$$

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[1] In this context, sustainability means ‘preserving and/or improving the level of production without degrading natural resources’ Eurostat (2017).

$$N_{\text{applied}} = \sum \text{mineral fertilizer,organic fertilizer}^{\text{a}}, \text{ soil additives, BNF.}$$

$$N_{\text{removed}} = \sum \text{marketed crops, fodder and forage crops, pasture.}$$

a = considering standard factors for losses due to N emissions from volatilization in housing and storage, and manure application to soil (=net).

1.1.2. Farm-gate balance (FarmB)

FarmB was added to German agri-environmental regulations in 2018 (StoffBilV 2017). At present, FarmB only applies to large livestock farms, but will likely be extended to almost all farms from January 2023. The aim is to meet the national sustainability target of a maximum surplus of 70 kg N ha^{-1} by 2030 (The Federal Government 2020). In FarmB, nutrient accounting is based on invoices, delivery notes, and product declarations for nutrients (e.g. mineral fertilizers, feedstuffs) or standard values (e.g. nutrient content of animal products, excretion factors). All products containing N or phosphates that enter the farm from external sources are considered 'inputs' and all products containing N and phosphates that leave the farm are considered 'outputs'. Gaseous losses are not considered, as FarmB is a gross calculation. BNF on arable land is considered an input, whereas atmospheric N deposition is not directly considered (equation (2)). The actual gross farm-gate balance threshold is an N surplus $\leqslant$175 kg N ha^{-1} as 3 year mean. Also, a farm-individual maximum N surplus can be calculated (StoffBilV 2017), which corresponds to the SoilB threshold (Klages *et al* 2017). In addition, loss factors are granted for organic fertilizers and roughage produce, and must be added to it. However, the impact is diminished by adding a 10% margin on the permitted maximum farm-individual balance value (StoffBilV 2017). FarmB aims to document nutrient flows on livestock farms in a transparent and comprehensible manner (BMEL 2019). The FarmB value is thus an indicator of the environmental pollution caused by N compounds, and is actually considered the most integrative and transparent indicator in nutrient management (Oenema *et al* 2003, Bach and Frede 2005, SRU 2015). Further indicators, e.g. farm NUE, may also be deduced from FarmB (Löw *et al* 2020).

$$\text{FarmB}\ \left[\text{kg N ha}^{-1}\right] = \frac{N_{\text{imported}} - N_{\text{exported}}}{\text{utilized agricultural area}}. \tag{2}$$

$$N_{\text{imported}} = \sum \text{mineral fertilizer, organic fertilizer}^{\text{a}}, \text{ soil additives, seeds and planting material, fodder, animals, BNF.}$$

$$N_{\text{exported}} = \sum \text{plant products, animal products, animals, mineral fertilizer, organic fertilizer}^{\text{a}}, \text{ soil additives, seeds and planting material.}$$

a = organic fertilizer quantities produced (=gross).

1.1.3. Fertilization planning (FertP)

Since 2020, FertP is the main regulatory control approach for on-farm fertilizer management and for enforcement of Nitrates Directive in Germany (Awater-Esper 2019). This is in accordance to Nitrates Directive Article 5 and annex III defining the required component of action programs for vulnerable zones (European Commission 1991). Germany applies the Nitrates Directive at national level, and has designated regions with elevated nitrate pollution where fertilization is limited to 80% of the fertilization demand calculated according to FertP (DüV 2020).

FertP is a mandatory, site-specific tool based on crop-specific nutrient demand values and nutrient availability from soil and previous crops. Depending on farm-specific (quantitative and qualitative) yield potential for the preceding 5 year period, individual on-farm nutrient demand can differ from the standard value. Actual fertilization demand is reduced by standard values representing the nutrient supply from soil, due to soil type or previous organic fertilization, based on soil analysis for plant-available N in spring. An overview of the exact methodology can be found in equation (3) and in section 2.1. The resulting fertilization demand for a growing season can be met by organic, organo-mineral, and mineral fertilizers, but must not be exceeded. Thus, FertP establishes a farm-specific maximum total N application. However, this requires knowledge of the nutrient concentration in the applied fertilizers. For manure or digestate, standard values from DüV can be used as an alternative to laboratory test results (DüV 2020). Contrasting SoilB, additional deductions (=minimum effectiveness) are calculated for N from organic fertilizers applied.

$$\text{FertP}\ \left[\text{kg N ha}^{-1}\right] = N\ \text{demand}_{\text{crop}} + \text{additions} - \text{deductions}. \tag{3}$$

$$\text{Additions} = \sum \text{yield difference}^{\text{a,b}}, \text{ covering}^{\text{a}}, \text{ difference in raw protein}^{\text{b}}.$$

$$\text{Deductions} = \sum \text{yield difference}^{\text{a,b}}, N_{\text{available}} \text{ in the soil}^{\text{a}}, N_{\text{residual}} \text{from organic fertilizers in previous years}^{\text{a,b}}.$$

$$N_{\text{residual}} \textit{from soil reserve}^{\text{a,b}}, N_{\text{residual}} \text{from BNF}^{\text{b}}, \text{ previous crops}^{\text{a}}, \text{ difference in raw protein}^{\text{b}}$$

Table 1. Comparison of the three agri-environmental approaches considered regarding time, space and indicator usage.

Indicator, legal reference	Statutory framework	Temporal scale, dimension	Spatial scale	Reference unit	Aim for indicator use
Fertilization planning, §4 DüV (2020)	Nitrates Directive[a], NEC Directive[b, c]	*Ex ante*, 1 year	Parcel, or homogeneous land unit	Area (ha)	Planning and consultancy, monitoring, control
Soil surface balance, §8 DüV (2017)	EC Nitrates Directive[a], NEC Directive[b]	*Ex post*, 3 year	Agricultural area utilized	Area (ha)	Benchmarking, monitoring, control
Farm-gate balance, §6 StoffBilV (2017)	German Fertilizer Law[d], §11a	*Ex post*, 3 year	Farm	Farm, area (ha)	Benchmarking, monitoring, control

[a] European Commission (1991).

[b] European Commission (2001).

[c] European Commission (2016).

[d] DüngG (2009).

a = valid for arable crops and vegetable growing.

b = valid for grassland, permanent pasture and multi-cut fodder crops.

Under the Nitrates Directive, fertilization planning is the main control approach for limiting N inputs to EU farms. Nutrient balancing is currently only mandatory in Switzerland, Romania, and partly in Germany, but fertilization planning must be recorded in all EU countries (Klages *et al* 2020a). In the Netherlands, N balances are drawn up at the farm-gate level of dairy farms. This is not mandatory but an agreement between the milk processing industry and producers, requiring digital reporting of N balances ('ANCA tool') as a precondition for market access to the national milk processing industry (Aarts *et al* 2015, Holster *et al* 2015, Klages *et al* 2020a).

1.2. Research gap and objectives

In previous studies, FADN data have been used to generate farm-gate N balances for certain regions in EU Member States, e.g. in Flanders, Belgium (Nevens *et al* 2006), and in Hesse and Baden-Württemberg, Germany (Gamer and Zeddies 2006, Bach 2013, StickstoffBW 2015, 2017). In these studies, mineral fertilizer quantities were derived from fertilizer costs using N-coefficients, as documentation of detailed quantities only began in 2016/17. The present study is unique in using (a) exact data on the quantities of mineral fertilizers applied and (b) a broad spectrum of German farm types to (c) qualitatively and quantitatively compare and evaluate three important past and future agri-environmental performance indicators embedded in German regulatory law.

The overall aim was to show the systematics and identify similarities and differences in the three performance indicators for farm nutrient management (table 1), qualitatively with regard to robustness and integrity[2], and quantitatively with regard to maximum permitted N fertilizer application rate. Accurate nutrient balances and fertilization plans were generated, primarily based on farm accounting records, and used to estimate discrepancies between actual application rates of N fertilizers and maximum permitted rates for the farm type according to the regulatory performance indicator. Thus, (a) the strictness of the approaches was evaluated and (b) reduction requirements in fertilizer use or scope for action on different farm types was identified, (c) taking into consideration data uncertainty and parameter reliability of the different parameters of the approaches. The hypotheses tested were:

Hypothesis 1 (H1.). Different performance indicators can be used to establish restrictions on fertilizer inputs which lead to comparable results in theory.

Hypothesis 2 (H2.). The design of the requirements based on the different indicators leads to differing impacts in practice.

Hypothesis 3 (H3.). The underlying data and assumptions used to compute the indicators lead to systematic differences of the three indicator-based regulatory approaches in terms of data uncertainty and reliability.

Hypothesis 4 (H4.). The conclusions on the hypotheses H1 to H3 vary according to farm types.

2. Material and methods

2.1. Data

We used FADN data covering approximately 10 000 farms in Germany, representing different farm types and regions with comprehensive structural and financial data. Prior to analysis, an accuracy check on all

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[2] Integrity in this context means incorruptibility and accuracy of an approach according to guidance in the Paris Agreement UNFCCC (2016).

data was made using a plausibility program provided by the Federal Ministry of Food and Agriculture (BMEL). For details, see BMEL 2018a, 2018b.

From the data, six farm types were identified using the EU/BMEL farm typology based on financial outputs: (a) arable farms, (b) dairy farms, (c) other cattle and grazing livestock farms, (d) mixed production systems, (e) pig and poultry farms, (f) permanent crop farms. For pig and poultry farms, only agricultural farms having UAA are listed, and not industrial farms. The key data for the farm types were weighted using type-specific extrapolation factors, to ensure consistency with sectoral totals (Hansen *et al* 2009, Haß *et al* 2020). These factors, derived from the national farm survey (DESTATIS 2017), were stratified using farm size, financial output, and farm type, to reduce the standard error in the results. SoilB, FarmB, and FertP were calculated to determine the permitted N fertilizer input for the financial year 2018/2019[3], that may be applied either by mineral fertilizers or by the plant-available organic fertilizers. Farms with animals may reach the limit with organic fertilizers alone.

Since previous 5 year yield is considered for FertP, only farms with long-term representation in FADN were included ($n = 6112$). The required parameters are approach-specific and differ in terms of data reliability. FarmB and SoilB use similar data, but the system boundaries (farm-gate or soil surface) differ. FertP uses another logical access to the data, but the parameters used are also quite similar to FarmB and SoilB. Assessment of parameter- and approach-specific data reliability, focusing on data origin, revealed differences (table 2). For further details on the source of data and the implementation based on German FADN see table A1 (available online at stacks.iop.org/ERL/16/055009/mmedia).

2.2. Statistical analysis

For explorative data analysis, the equivalent functions in Microsoft Excel Professional Plus 2010 were used. Mean and standard deviation for different farm types were calculated based on the functions in SAS (*SAS 9.4*) commercial statistics software.

3. Results

The impact of the respective performance indicators (as kg N ha^{-1}) was calculated. Farm type-specific exceedance of the maximum surplus of 50 kg N ha^{-1} for SoilB, and of the maximum surplus of 175 kg N ha^{-1} and the farm-individual maximum surplus for FarmB, as legally binding thresholds, was then identified (DüV 2017, StoffBilV 2017). We also compared the amount of N applied above the N fertilizer requirement according to FertP, where the threshold value is the balance between foreseeable N requirements of the crops and the N supply to crops from soil and fertilizers. Land application of N fertilizer must not exceed the calculated N fertilizer requirement, which can be interpreted as a threshold level of zero.

Figure 1 shows the results of FarmB and SoilB for representative farms in the FADN network, as boxplots (10th to 90th percentile). For FarmB, pig and poultry farms (119 kg N ha^{-1}; mean surplus) and dairy farms (95 kg N ha^{-1}) had considerably higher N surpluses than the other farm types. For SoilB, only pig and poultry farms (76 kg N ha^{-1}) showed distinctly higher N surpluses. Both approaches revealed large variations in N surplus, even within farm type. However, due to the high gross N surplus in FarmB, the N input-limiting effects of the two approaches differed considerably. Figure 2 shows N applied compared with N permitted according to FertP, where values exceeding the 0-line indicate the exceedance of permitted N input thresholds and values below show that the permitted N input is not fully utilized.

The pattern for FertP and SoilB was generally similar (figure 2). For dairy farms (30%, 12 kg N ha^{-1}; share of affected farms of this type, mean N reduction requirement related to total farm area of the farm group), permanent crop farms (30%, 10 kg N ha^{-1}) and arable farms (16%, 6 kg N ha^{-1}), FertP was the most limiting approach. SoilB was most demanding for pig and poultry farms (68%, 35 kg N ha^{-1}), mixed production systems (28%, 11 kg N ha^{-1}), and other cattle and grazing livestock farms (18%, 8 kg N ha^{-1}) (figure 2). On average for the agricultural sector, 27% of the farms were affected with a mean reduction requirement of 10 kg N ha^{-1} for FertP, whereas the corresponding values were 23% and 9 kg N ha^{-1} for SoilB.

The current threshold in FarmB (175 kg N ha^{-1} surplus) was not demanding for most of the farm types. Only pig and poultry farms showed considerable surpluses greater 175 kg N ha^{-1} (21%, 12 kg N ha^{-1}) (figure 3). On average for the agricultural sector, 6% of farms were affected by the FarmB threshold, with a mean reduction requirement of 2 kg N ha^{-1}. However, the farm-individual determination of the maximum N surplus gave comparable reduction requirements to FertP and SoilB. On average for the agricultural sector, 30% of the farms were affected by FarmB farm-individual threshold, with a mean reduction requirement of 15 kg N ha^{-1}. Pig and poultry farms (64%, 41 kg N ha^{-1}) were most affected, followed by dairy farms (34%, 19 kg N ha^{-1}) and other cattle and grazing livestock farms (25%, 12 kg N ha^{-1}). Arable farms (17%, 5 kg N ha^{-1}) and permanent crop farms (8%, 4 kg N ha^{-1}) were least affected. For details of all N reduction requirements, see table A2.

The maximum N fertilizer input permitted by FarmB, SoilB, and FertP varied greatly between farm types, and showed differences in distribution among

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[3] The majority of farms (95%) base their accounts on the fiscal year.

Table 2. Overview of the required parameters in the three performance indicators and data reliability.

Parameter	Indicator			Characteristics
	Farm-gate balance (§6 StoffBilV 2017)	Soil surface balance (§8 DüV 2017)	Fertilization planning (§4 DüV 2020)	Data reliability[a] score
Inputs				
Mineral fertilizer	X	X	X	1
Manure: imported	X	X	X	0
Manure: internal use	n.a.	X	X	−1
Digestate: imported	X	X	X	0
Compost, sewage sludge, other organic fertilizer: imported	X	X	X	1
Fodder: imported	X	n.a.	n.a.	1
Livestock	X	n.a.	n.a.	0
Biological N fixation	X	X	X	−1
Seeds, plant material	X	n.a.	n.a.	1
Outputs				
Yield of marketed crops	X	X	X	1
Yield of fodder and forage crops for farm-internal use	n.a.	X	X (forecast)	−1
Livestock	X	n.a.	n.a.	0
Animal products	X	n.a.	n.a.	1
Manure: exported	X	X	X	0
Digestate: exported	X	X	X	0
Seeds, plant material	X	n.a.	n.a.	1
Gaseous N losses[b]	n.a.	X	X	0
Further location, crop and farm characteristics				
Cultivated area	X	X	X	1
Crop- and yield-specific N demand value: marketed crops	n.a.	n.a.	X	1
Crop- and yield-specific N demand value: fodder and forage crops	n.a.	n.a.	X	−1
N supply from manure application in previous year	n.a.	n.a.	X	0
N supply from soil				
N available in soil (N_{min})	n.a.	n.a.	X	−1
Humus content	n.a.	n.a.	X	−1
Previous crops, catch crops	n.a.	n.a.	X	1
Crop residues	n.a.	X	X	−1

Atmospheric N deposition is reported in an appendix to the FarmB according to (StoffBilV 2017), but is not part of the calculated balance.

[a] Data reliability score: high, e.g. receipt-based = 1; medium = 0; low, e.g. self-reported by farmers and hard to verify = −1.

[b] Gaseous losses due to N emissions from volatilization in animal housing and manure storage, manure application to the land, and total N emissions from animal excretion on pasture.

n.a. = not applicable, not an element of the respective indicator.

farm types. Farms with livestock were generally more affected by statutory thresholds. Regarding the approach-specific need for reduction, impacts of the three approaches on the permitted N input showed strong similarities, especially for SoilB and FertP. Unsurprisingly the FarmB generalized threshold level of 175 kg N ha^{-1} was meaningless for most farms, but the farm-individual threshold gave more restrictive results, especially for farms with livestock.

Table 3 shows selected parameters used in calculation of the three performance indicators and an assessment of associated data uncertainties and reliability. Uncertainty is subject to the accuracy of determination of nutrient amounts, based on area, volumes of fertilizers, and farm products, and specific nutrient contents. By defining the uncertainty margin based on legal requirements on the accuracy of declared nutrient contents (Klages *et al* 2017), the effects on the respective performance indicator were revealed. The baseline scenario for FarmB, SoilB, and FertP shows aggregated average values for the agricultural sector calculated based on German FADN data

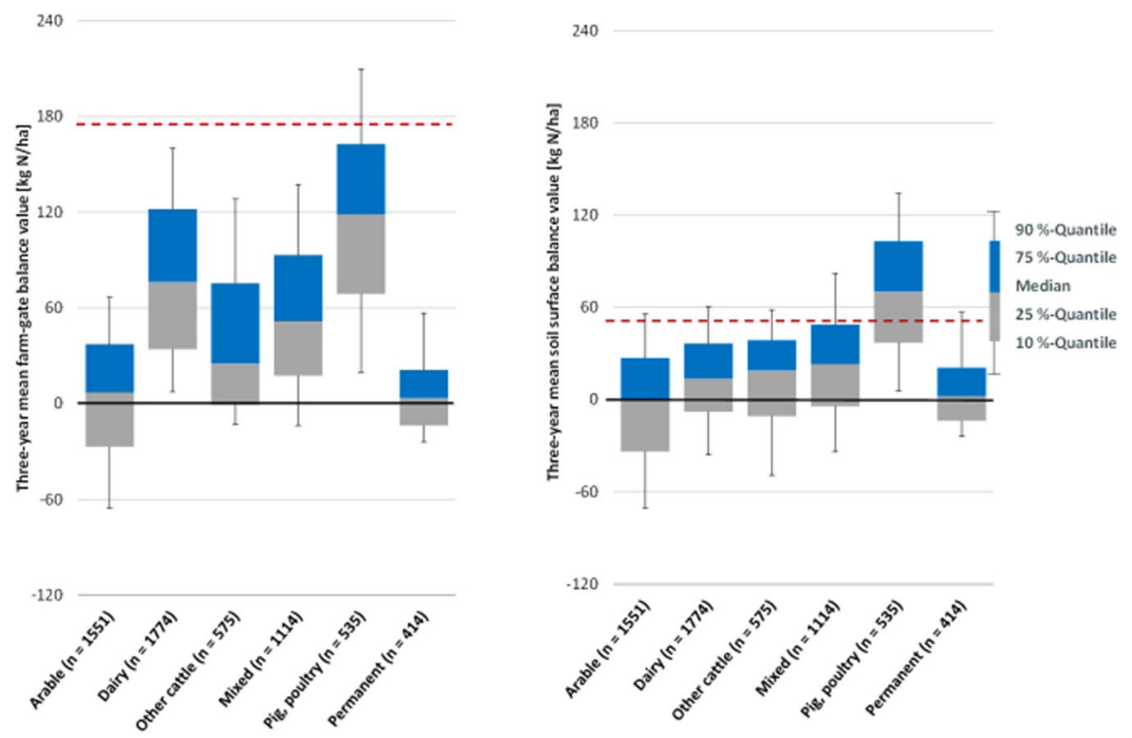

Figure 1. Three year mean farm-gate balance value (FarmB, left) and soil surface balance value (SoilB, right) of the farm types studied. (Dashed lines = legally binding thresholds.)

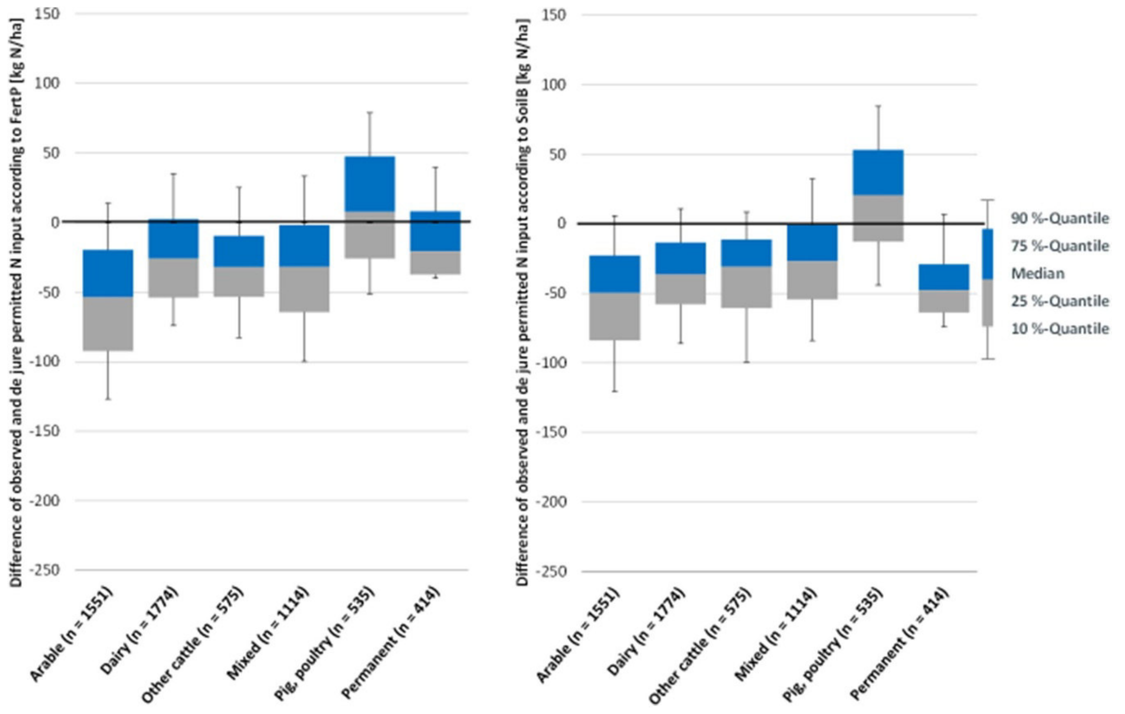

Figure 2. Differences of observed nitrogen (N) input and *de jure* permitted N input according to fertilization planning (FertP, left) and soil surface balance (SoilB) with a threshold of 50 kg N ha^{-1} (right). (Difference = observed minus *de jure* permitted N input.)

(table 3). Data reliability is ranked based on the level of documentation, from receipt-based accounting of traded commodities to estimates of farm-internal N flows (The WAgriCo Project 2008).

4. Discussion

In the following, parameters required for calculating FarmB, SoilB, and FertP and the respective data

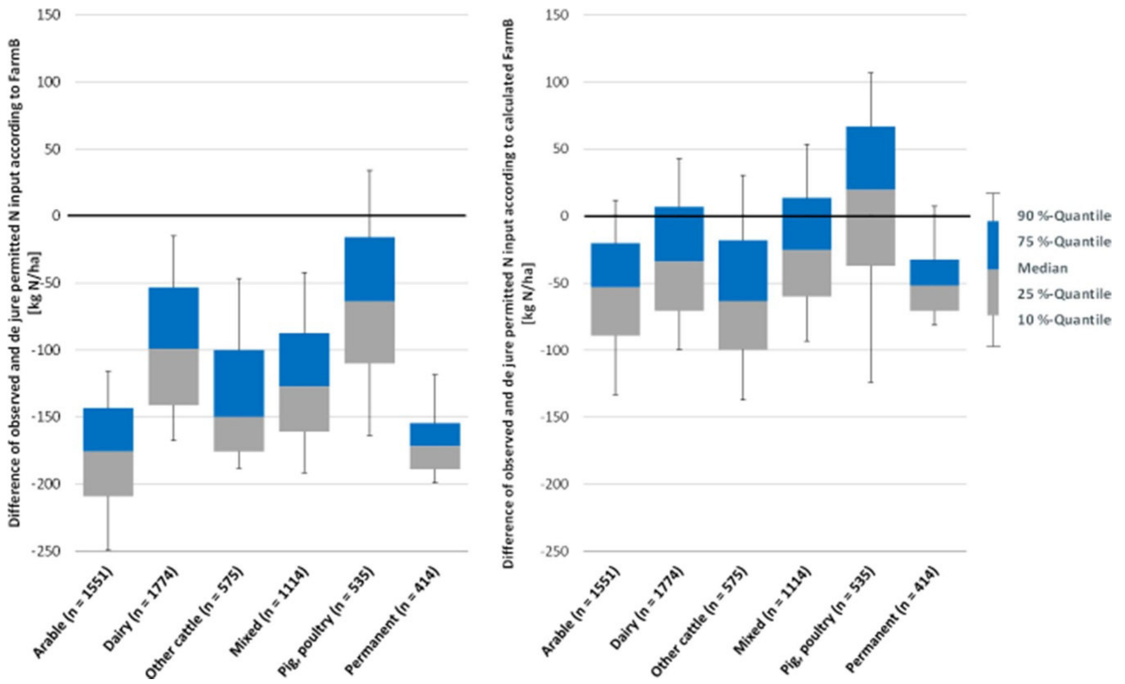

Figure 3. Differences of observed nitrogen (N) input and *de jure* N permitted N input according to farm-gate balance (FarmB) with a threshold of 175 kg N ha $^{-1}$ (left) and with farm-individual determination of the maximum N surplus (right). (Difference = observed minus *de jure* permitted N input.)

uncertainty and reliability are compared. First, elements common to three or two of the approaches are presented, followed by elements specific to a single approach. Consequences for the different performance indicators are then discussed.

4.1. Elements of all three approaches

Data on UAA, area of cultivated crops, and number of livestock are required for all approaches, in order to calculate related nutrient amounts, check the data for plausibility, or relate the result to cultivated area.

4.1.1. Mineral N fertilizer

This input shows high data certainty deriving from defined nutrient contents for mineral fertilizer. Receipt-based reporting of fertilizer purchases provides high reliability for this key element of N input. An important condition for verification is the control of enterprises involved in fertilizer sales.

4.1.2. Manure and digestate imports and exports

Nutrient amounts in organic fertilizers, imported or exported, can be either determined by laboratory analysis or calculated based on standard excretion factors for pre-defined livestock categories and standard factors for gaseous housing and storage losses of N, predominantly ammonia (DLG 2016, DüV 2020). These values are used for the declaration on receipts for exported amounts. There is no fast and reliable method for determining nutrients in manure on the fly, except NIRS (Millmier *et al* 2000, Huang *et al* 2007), which is not yet accepted as a standard method in Germany (Severin *et al* 2019). Calculations based on N excretions per livestock unit and gaseous losses, or based on testing of samples, lead to high variability. Thus, data uncertainty is relatively high. Data reliability is also limited, because classification of livestock categories and manure sampling are performed by farmers. For FarmB, exports and imports are part of the balance. For SoilB and FertP, exports are deducted from the amount of farm-internal manure and digestate, and imports are added to the remaining internal amount. While exporting farms might be keen to declare high amounts of nutrient exports, importing farms are reluctant to accept more nutrients declared than they receive. These opposing interests help to control the consistency of declarations. A precondition is the inclusion of all farms in nutrient accounting, including livestock farms and biogas facilities with no farmland. The latter are only addressed by FarmB (StoffBilV 2017). Organic fertilizers imported from other sectors, such as compost and sewage sludge, play a minor role in total N balances and are not represented in table 3. These fertilizers are regularly analyzed before export to farms.

4.1.3. Biological N fixation

While data on the area of legume crops are quite exact and reliable, yield-dependent rates of BNF vary, so the data are more variable and less reliable. For grassland and mixed green forages, the need to determine the proportion of leguminous plants such as clover, and the yield increases uncertainty and reduces data reliability. The different ways of assessing the amount

Table 3. Data uncertainty and reliability and impacts on the results of the three performance indicators.

Balance elements	FarmB	SoilB	FertP elements	FertP	Data uncertainty	Data reliability
	kg N ha^{-1} (3 year mean)			kg N ha^{-1} * a	(%)	Score
			Soil- and crop rotation-specific N supply	**48**	n.a.	n.a.
			Previous crops	7	−0/+0	1
			Biological N fixation	13	−20/+20	0
			Humus content	0.02	−20/+20	−1
			Plant-available soil N in spring (N_{min})	22	−20/+20	−1
			Manure (previous year)	6	−20/+20	0
			Crop residues	0.1	−10/+10	0
			Catch crops	0.01	−20/+20	0
Inputs	**156**	**164**	**Inputs**	**125**	n.a.	n.a.
Mineral fertilizer	96	96	Mineral fertilizer applied	88	−1/+1	1
Purchased fodder	48	n.a.		n.a.	−5/+5	1
Animal excretions (net N)	n.a.	48	Manure applied (effective N)	35	−20/+20	0
Digestate	5	5	Digestate applied (effective N)	2	−20/+20	0
Biological N fixation	6	15		n.a.	−20/+20	−1
Seeds, plant material	2	n.a.		n.a.	−5/+5	1
Outputs	**98**	**136**	**N demand** (crop- and yield-specific)	**191**	n.a.	
Marketed crop products	68	68	N demand marketed crops	97	−5/+5	1
Marketed plant by-products	1	1		n.a.	−10/+10	0
Fodder and forage pro-duced and used on-farm	n.a.	67	N demand fodder and forage crops produced and used on-farm	94	−20/+20	−1
Animals[a]	11	n.a.		n.a.	−10/+10	0
Animal products	14	n.a.		n.a.	−5/+5	1
Organic fertilizer	5	n.a.		n.a.	−20/+20	0
	n.a.	n.a.	**N fertilizer requirement**	**150**	n.a.	n.a.
Balance value[b]	**56**	**25**	**N inputs—N fertilizer requirement**[b]	**−25**	n.a.	n.a.

(Continued.)

Table 3. (Continued.)

Balance elements	FarmB	SoilB	FertP elements	FertP	Data uncertainty	Data reliability
	kg N ha^{-1} (3 year mean)			kg N ha^{-1} * a	(%)	Score
Data uncertainty (min./max.) [kg N ha^{-1}][c]						
min./max deviation of inputs	−6/+6	−15/+15	min/max deviation of N supply and input	−16/+16	n.a.	n.a.
min./max deviation of outputs	−5/+5	−17/+17	min/max deviation of N demand	−24/+24	n.a.	n.a.
min./max deviation of balance	−11/+11	−31/+31	min/max deviation of (inputs—fert. requirements)	−40/+40	n.a.	n.a.
Data reliability score[d]						
Input	0.7	0.5	N supply and input	0.4	n.a.	n.a.
Output	0.8	0.0	N demand	0.0	n.a.	n.a.
Total elements of balance	0.8	0.3	Total elements of FertP	0.2	n.a.	n.a.

FarmB and SoilB parameters as three-year means (2016/17–2018/19), FertP as annual means (2018/19), with plant requirements based on average yield in the past 5 years.

[a] Balance of animals purchased and sold or lost.

[b] Positive values indicate a surplus, negative values a deficit.

[c] Variability of data, esp. nutrient contents, range in %.

[d] High, e.g. receipt-based = 1; medium = 0; low, e.g. self-reported by farmers and hard to verify = −1 (see table 2).

n.a. = not applicable, not an element of the respective indicator.

of BNF in the three approaches lead to additional variation.

4.1.4. Yield of marketed crops

Marketed crops are reported on the basis of receipts, so that volume and commodity type are defined. Therefore, data certainty and reliability are relatively high. If protein content is not reported, standard values for N content must be used. Problems may arise if the commodity type is not sufficiently specific for attributing the correct nutrient content. In FarmB, marketed crops are the most important element of N exports. In SoilB, yields are normally not differentiated into marketed crops and those use as fodder and forage. In FertP, yields are the basis for deriving crop- and yield-specific N demand. Information on yields of marketed crops can help to check yield data in SoilB and FertP for plausibility.

4.2. Elements of SoilB and FertP

4.2.1. Manure for internal farm use

For this element of SoilB and FertP, the same constraints as for manure and digestate imports and exports apply (see above). In intensive livestock farms, N amounts in manure are high, and thus also uncertainty of SoilB and FertP is high. The most common method for determining the amount of nutrients is the calculation based on standard factors. As there is no receipt-based accounting and mutual control between farms, as is the case for export and import of manure, declared amounts of nutrients in on-farm animal excretions and digestates may be even less reliable compared to traded manure.

4.2.2. Yields of fodder and forage crops for internal farm use

Fodder and forage are important N exports in SoilB of livestock farms, and an important basis for calculation of N demand in FertP. Crop area is reliably declared, but yields are difficult to quantify and vary widely, especially for forage crops and grassland. As internal flows, amounts are not documented by receipts, and even at farm level exact information is difficult to obtain. For dairy and cattle farms with high amounts of farm-internal production and use of forage, nutrient uptake by forage crops is regularly overestimated. Analysis of SoilB data within the WAgriCo-Project showed that higher proportions of maize and grassland in total farm land lead to high N removals in SoilB, which is not plausible in relation to the livestock herd and its N excretions (The WAgriCo Project 2008). In farm groups with forage production, N removal estimated in SoilB was up to 28 kg N ha^{-1} above an improved estimate of forage production. Quantitative estimation of forage produced and forage losses clearly results in high uncertainty, making it difficult to assess the actual amount of forage produced and used on-farm. Thus, SoilB can be considered non-robust because of the estimation of yields, especially for roughage (Baumgärtel *et al* 2007). An evaluation of DüV 2007 in 2012 showed overestimation of forage amounts by on average 40 kg N ha^{-1} on around 10 000 dairy and cattle farms (DüV 2007, Wendland *et al* 2012). Consequently, a requirement for verification of nutrient uptake by forage crops through cross-checking with forage needs of the farm´s animal herd was introduced in 2017 (DüV 2017). However, forage losses of 15% for field crops such as green maize and 25% for grassland were allowed, moderating the restrictions resulting from stricter nutrient balancing for dairy and cattle farms. A large proportion of these forage losses occur on the cultivated area and thus do not represent a nutrient export. Furthermore, off-site forage losses in storage and housing are collected and usually returned to the land (Klages *et al* 2017).

4.3. Elements of FarmB

4.3.1. Fodder imported

Purchased fodder and forage is documented through receipts, so volume and commodity type are determined accurately and reliably. However, nutrient content may vary, especially in forage. If protein content is not reported, standard values must be used, which adds uncertainty.

4.3.2. Seeds and plant material

This element is of minor importance for the total balance. Input can be either be documented by receipts, or estimated based on the area of cultivated crops and standard values.

4.3.3. Livestock and animal products

Import and export of living livestock, animal losses, and export of animal products such as milk and eggs are reliably reported by receipts, from which number or volume and commodity type are known. For livestock, data on specific weight are sometimes lacking, so weight categories must be applied, adding uncertainty. Animal products sold are normally well documented, for milk including regular testing of protein content. In all other cases, standard values for N content in livestock and products are used for calculating the total amounts, which are comparatively certain and reliable.

4.4. Elements of FertP

4.4.1. Crop- and yield-specific N demand values

Setting specific nutrient demand values is crucial, as these values differ on national (Taube 2018) and European level (Nicholson *et al* 2018, Klages *et al* 2020a). In Germany, higher demand values than in the previous regulatory framework at regional level now apply (DüV 2020). Experts claim that the demand values used for FertP are too high, which might lead to systematic overfertilization in some cases (Taube 2018). The differences are not always apparent, due to different methodologies, and should be further evaluated.

4.4.2. Yields of marketed crops and fodder and forage crops

Consideration of previous 5 year yield for FertP is another crucial issue. An unwarranted increase in farm yield, which is difficult to monitor, could lead to upward adjustment of the calculated N requirement, creating corruptibility that may undermine the integrity of the approach. Problems of data uncertainty and reliability mentioned above for fodder and forage crops also have to be considered.

4.4.3. N supply from manure application in previous year

From this N amount, 10% is considered in FertP. Data certainty and reliably are as for manure for internal farm use.

FertP also considers different kinds of N supply from soil:

4.4.4. Plant-available soil N in spring (N_{min})

The amount of plant-available N, usually determined for 0–90 cm soil depth (less for some vegetable species) at the beginning of the growing season (N_{min}-value) is fully considered in FertP. The magnitude of the N_{min}-value depends strongly on external factors such as location, weather, and sampling season, as well as sampling method, and transport to the laboratory. However, N_{min}-value is often taken from officially published charts, but farm-specific measurements should be preferred. Due to high spatial variability found in many studies, sampling is difficult and the results are questionable (Baumgärtel 1993, Stenger *et al* 1996, Lorenz 2004).

4.4.5. Humus content

N mineralization in soil is considered using a few categories of soil humus content applied by farmers. Testing for soil organic carbon content is not mandatory. Thus, data uncertainty is high and reliability limited.

4.4.6. Previous crops, catch crops

N deriving from previous crops, such as legumes and catch crops, are included in FertP using simple standard values. Calculated values based on crop area are accurate and reliable, but might not depict real N provision by previous crops, which depend also on yields and soil management. For catch crops, the differentiation between harvested and unharvested areas is difficult to verify, so data reliability is more limited.

4.4.7. Crop residues

Crop residues of vegetables are considered in a similar way to residues of previous arable crops.

4.5. Consequences of data uncertainty and limited reliability for the three performance indicators

In the following, the consequences of data uncertainty and limited reliability is discussed, focusing on potential for improvement of single parameters in order to maximize the benefit of the indicators for future use.

The limited certainty and reliability of farm-internal flows, primarily manure from farm livestock and fodder and forage produced and used on-farm, strongly reduce the certainty and reliability of SoilB and FertP. Factors for N losses and plant availability in manure (manure N efficiency) are individually adjustable (Klages *et al* 2020a). The amount of farm-internal fodder and forage is not strictly recorded and difficult to verify. Farmers themselves often do not have exact measurements of these amounts, especially in case of forage production. Thus, estimations are used. However, since SoilB has been abolished as part of DüV 2017, standard data for calculating forage intake by ruminant animals and horses are no longer available (DüV 2017, 2020). Consequently, also FertP lacks a legal basis for improved, plausible estimation of forage yields.

For FertP, plant-available soil N in spring (N_{min}-value) as part of soil- and crop rotation-specific N supply increases uncertainty and reduces reliability. Mandatory samplings at higher frequency and in higher numbers on each parcel could contribute to higher certainty about mineralized N amounts in FertP. However, to increase the reliability score, the sample should be taken by independent experts. Further, the calculation factors for N requirements of crops are critically discussed for being presumably overestimated (Taube 2018). Additionally, the N fertilization requirements determined in FertP may be exceeded through exemptions (poor plant development, adverse weather conditions), although not by more than 10% of permitted fertilizer N input (DüV 2020). Other important elements used in SoilB and for calculation of FertP, i.e. mineral N fertilizer input and yields of marketed crops, are quite certain, reliable, and verifiable on the basis of receipts.

Overall, data uncertainty is high, expressed as estimated minimum and maximum deviation in calculated values of total inputs, outputs, and the balance value for SoilB, and in N supply and input, N demand, and the difference between N inputs and fertilization requirements in FertP. For the sectoral average calculation shown in table 3, the estimated maximum deviations cumulate to 31 kg N ha^{-1} for SoilB and to 40 kg N ha^{-1} for FertP. The data reliability score with values between -1 and $+1$, is 0.3 for SoilB, and 0.2 for FertP. For performance indicators used in regulations, these results appear unsatisfactory.

FarmB relies mainly on receipt-based flows of mineral N fertilizer input, purchased fodder and forage, yields of marketed crops, and livestock and animal products. Elements such as BNF by leguminous crops and import/export of manure are difficult to determine, thus contributing to uncertainty and limited reliability. However, these are elements of all three approaches. In table 3, the estimated maximum deviations for the sectoral average FarmB cumulate to 11 kg N ha^{-1} and the data reliability score is 0.8. These superior results for FarmB as a performance indicator are because farm-internal N flows are not included in calculations, avoiding uncertainties and lack of reliability for these flows. FarmB shows added value in nutrient management, and appears most appropriate as a performance indicator for regulations.

In this context, SRU *et al* (2013) argued that the regulatory approach to nutrient balancing should be applied at farm-gate level, as SoilB offers great scope for inaccuracies and even manipulation. Becker and Beisecker (2017) noted that gross nutrient balances would be simpler to compile, fairer, and more comprehensible. The unique advantage of FarmB is that it is largely based on farm accounting data, so it can provide objective, standardized results (Wüstholz and Bahrs 2013). This provides high robustness, high transparency, and low manipulability (Scheck and Haakh 2008, SRU *et al* 2013, Becker and Beisecker 2017). The greater controllability of the information reported could improve enforcement by control authorities (SRU *et al* 2013). Thus SRU (2015) strongly recommends a gross approach, to make total on-farm N flows visible to farmers, and no deduction of environmentally relevant ammonia losses *a priori*.

FarmB is recognized as an integer approach by scientific, consulting, and official institutions, but can be improved to make the indicator values more robust and establish it as a mainstay of nutrition management and mandatory regulation (see also Klages *et al* (2017)), through:

- Improved declaration and standardized documentation on nutrient contents in traded fertilizers, feed, and forage, with trade registers for these commodities.
- Uniform documentation of quantities and qualities of traded manure, including small quantities (e.g. in a manure trade register).
- Improved methodology for estimation of BNF.
- A uniform and comprehensible evaluation tool for meaningful mandatory regulation.
- Sanctions for exceeding the maximum balance values.
- Enabling control authorities to monitor also non-agricultural actors of fertilizer and fodder trade, in order to verify nutrient flows of purchased farm inputs.

In Germany, an extension of an mandatory FarmB to all farms >20 hectares or with >50 livestock units is envisaged by 2023 latest (StoffBilV 2017, The Federal Government 2019). As 45% of farms cultivated less than 20 hectares in 2016, representing only 7% of German agricultural area (DESTATIS 2019), the decision to keep small farms outside the scope of FarmB helps to avoid bureaucratic burden. In order to close loopholes of this regulation, small farms importing manure from larger farms are now obliged to establish a FarmB, too. Currently, an exceeding of the determined N fertilizer demand may entail a fine up to € 50 000, an excessive FarmB surplus may result in the order of a consultation within 6 months. However, the reporting of FarmB is not part of Cross Compliance, as it is not based on EU legislation.

This study clearly showed that the current uniform threshold of 175 kg N ha^{-1} in FarmB in Germany (StoffBilV 2017) is no challenge for most farms (figures 1 and 3), and will therefore not contribute to an increase in NUE. In fact, the introduced FarmB concept has to be seen as a first step. The determination of this unpretentious threshold was presumably set in order to get farms used to the novel procedure before scaling up, and is therefore politically rather than scientifically legitimized. The option of a farm-individual threshold value was offered to farmers alternatively in StoffBilV (2017). This target values lead to higher adaptation needs on livestock farms. The German Climate Action Program 2030 requires to make FarmB obligatory for most farms combined with a step-by-step alignment of the national FarmB with the target value of the sustainability strategy (70 kg N ha^{-1}) in 2030 (The Federal Government 2019). So, concepts already exist for gradually reducing the FarmB threshold, for example by means of a staggered reduction from 120 to 90 kg N ha^{-1} depending on the amount of organic fertilizers produced, as published in a project on behalf of the German Federal Environment Agency (Taube *et al* 2020). A reduction of FarmB, and, thus, N emissions in general, is achievable by reducing inputs or increasing outputs. N inputs may be reduced by N-reduced feeding or by lower fertilizer inputs, which is possible, e.g. through higher manure N efficiencies due to management (e.g. splitting of fertilization) or technical options, just like NIRS (Millmier *et al* 2000, Huang *et al* 2007), or injected application (Webb *et al* 2013, Mencaroni *et al* 2021), or precision farming (Chmelíková *et al* 2021). Outputs may be increased by higher manure exports or by production growth, although unit-related production levels for dairy, meat and field crops are already very high in Western Europe, and rather await challenges related to climate change (Gauly *et al* 2013, Mauger *et al* 2015, Vollmann 2016). Experiences of practical application of FarmB stem from voluntary water protection initiatives based on intensive technical advice using FarmB for benchmarking purposes (Scheck and Haakh 2008, SRU *et al* 2013, Becker and Beisecker 2017). Scaling up FarmB as an element of mandatory rules on national level poses difficulties. In the Netherlands, FarmB was previously used in the MINAS as the basis for regulation

(Schröder and Neeteson 2008), but MINAS has been abolished due to difficulties e.g. for farms trading manure in determining the N content of manure, or due to differences between soil types in the relationship between N surplus and nitrate concentration in groundwater (Oenema *et al* 1998). FarmB, as part of the 'ANCA tool', is currently a requirement for dairy farms in the Netherlands wishing to participate in the national dairy market (Aarts *et al* 2015). The focus is on good collaboration between government, research, and the dairy sector. Neighboring countries have difficulty adopting this approach due to greater heterogeneity of the dairy sector and the lack of a central database for (automatically) collecting and storing data (Oenema and Korevaar 2018). Calculation and reporting methods for FarmB are currently being revised, and a new, uniform evaluation method for FarmB will replace the existing complex target system in Germany.

5. Conclusions

We used three regulatory approaches (SoilB, FarmB, FertP) to calculate performance indicator values based on German FADN data, and compared the values against legally defined thresholds for limiting N fertilizer input. Impacts of requirements based on FertP (*ex ante* approach) coincided fairly well with those of SoilB, while impacts of requirements based on FarmB were low because this recently introduced approach has a less restrictive first step. With another evaluation system, impacts of FarmB could be increased. The results confirmed H1 that different performance indicators can be used to establish restrictions on fertilizer inputs with comparable results. The current design of FarmB supports H2, that in practice the design of requirements leads to differing impacts. Assessment of data uncertainties and reliabilities and their consequences for the three performance indicators showed large differences between SoilB and FertP with low certainty and reliability, due to greater reliance on farm-internal data and flows, and FarmB, with better data quality due to largely receipt-based accounting. This confirmed H3 that underlying data and assumptions affect data uncertainty and reliability of the three indicator-based regulatory approaches. Also, the farm type-specific quantitative analysis showed lower variances and consistent FarmB and SoilB values for arable farms, because their nutrient flows (fertilizers purchased, crops sold) are well-documented and reliable. In contrast, livestock farms showed exceeding indicator values and greater variances than other farm types, which supports H4. In a follow-up study, we aim to identify describing socioeconomic variables and farm characteristics of efficient nutrient management.

In the context of the latest DüV amendment in 2020 and the abolition of SoilB due to the COM´s concerns and, as a consequence, the decision of the European Court of Justice (2018) about the respective methodology, FertP will be of particular importance in Germany as a key approach for nutrient management to meet the requirements of EU Nitrates Directive. Germany, thus, follows a European trend, as nutrient balances are only obligatory in Switzerland and Romania (Klages *et al* 2020a). In its sentence, the European Court of Justice (2018) argues that the German SoilB allowed crop N requirements to be exceeded, through the permitted N surplus. The underlying concept in FertP is an implicit threshold value of zero, as fertilizer inputs shall meet, but not exceed the plant needs. For SoilB a threshold value of 50 kg N ha^{-1} is defined, as it relates fertilizer inputs to nutrient removals in harvested crops, which according to DüV coefficients are lower than plant needs. Further, in SoilB more of the total N from organic fertilizers is accounted for, compared to FertP. Thus, although the two approaches appear to define different levels of ambition at the first glance, the resulting restrictions are almost the same. In our analysis we found similar restrictive impacts on N input levels for the two approaches.

As nutrient balances are recommended as a key indicator of farm environmental performance, the abolition of SoilB is not clearly considered beneficial. However, FarmB has been introduced in German law and will be rolled out for most farmland. It seeks evidence of inputs and outputs, and thus provides a more reliable basis for evaluation of farm nutrient management and for tracing farm nutrient flows. In particular, FarmB allows to better manage the uncertainties in forage farms with regard to their uncertain forage quantities.

However, a discussion is ongoing in Germany on whether FertP as an obligatory performance indicator is sufficient and what FarmB will provide, apart from an additional bureaucratic burden. We argue that digital and receipt-based systematic documentation of nutrient flows along the value chain within FarmB can considerably improve data acquisition and reliability, and reduce data uncertainties. Cross-checking FertP with FarmB data can help improve data on internal farm flows, making interpretation of FertP more reliable. Through (AI-supported) analysis, SoilB can be generated from FertP and FarmB data, and anomalies, inefficiencies, and their causes can be detected and analyzed in time, improving information for farmers, enabling advisory services to be offered to specific target groups, and allowing control authorities to operate more efficiently. In order to understand what (a good) N indicator performance is related to, additional socio-economic factors should be considered and benchmarking of farm NUE should be performed. Thus, further investigations are required to determine the scope for NUE improvements on farm-level and to better understand the impacts of policy measures on nutrient management, and to assure a targeted proceeding of control authorities.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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APPENDIX

Table A1: Overview of the required parameters in the three regulatory approaches considered and implementation in the methodology used based on data from the Farm Accountancy Data Network (FADN)

Parameter	Implementation in the FADN	Note
Inputs		
Mineral fertilizer	Quantitative values in kilograms N per hectare	FADN data considers the different nutrient contents of fertilizers.
Manure: imported	Not considered	Monetary values cannot be clearly considered as purchased or sold manure.
Manure: internal use	Animal category- and management-specific N-excretion rates per head;	DüV (2020)
	Grazing in function of farm structure and management:	Neuenfeld et al. (2019)
	no pasturing for calves and bulls,	UNFCCC (2016)
	30% N excretions on pasture for dairy cows,	Löw et al. (2020)
	50% N excretions for heifers and other cows, horse, goat, sheep;	
	Usage of digestate as a function of sold energy crops	
Digestate: imported	Import of digestate as a function of revenues from energy crops, divided by prices and literature-based N-coefficients	StoffBilV (2017)
Compost, sewage sludge, animal meal: imported	Not considered	
Fodder: imported	Expenditure on animal-specific feed;	Bach (2013), updated with data for fiscal years 2016/17 to 2018/19 from Agricultural Market Information Company (2020).
	market-based feed-specific N cost factors;	
	Concentrates for cattle, horse, goat, sheep: 9.09 €/kg N;	
	Pig feed: 11.34 €/kg N;	
	Poultry feed: 12.14 €/kg N;	
	Roughage: 3.92 €/kg N;	
	Others: 8.08 €/kg N	
Fodder/forage: internal use		
Livestock	Balance of animals purchased and sold and lost; N-coefficients literature-based (cf. *Outputs*)	StoffBilV (2017)
Biological N Fixation	SoilB, FertP:	DüV (2020)
	crop- and grassland-specific fixation-factors;	StoffBilV (2017)
	FarmB:	Benke (1992)
	crop-specific fixation-factors;	Stoll (1991)
	Grassland: in function of the total N input, from high (60 kg N/ha) BNF (<60 kg N/ha) to no BNF (>190 kg N/ha) (*FertP*)	Dyckmanns (1986)
Seeds, plant material	Imported seed for potatoes, maize, cereals and grain legumes;	StoffBilV (2017)
	Crop-specific seed amounts and N-content, N-coefficients literature-based	Quade (1993)
		KTBL (1992)

Parameter	Implementation in the FADN	Note
Outputs		
Yield of marketed crops	Crop-specific revenues, prices (€/dt), N-coefficients literature-based	DüV (2020) LfL (2019) Ehrmann (2017) Gamer & Bahrs (2010)
Yield of fodder and forage crops for farm-internal use	Crop-specific cultivated area, N-coefficients literature based;	DüV (2020)
	Forage crops: standard yields for maize and fodder crops;	LfL (2019)
	Grassland: yields derived from mean N intake of ruminants from fodder and forage crops under consideration of traded forage amounts and under consideration of standard factors for losses of unutilized feed, with a minimum yield of 40 dt dry matter/ha	DüV (2017)
Livestock	Balance of animals purchased and sold and lost, N-coefficients literature-based	StoffBilV (2017)
Animal products	Milk: milk revenues, prices (€/dt), sold dairy product quantities, N-coefficients literature-based; Assumptions on CP-content based on the usual product range: Dairy products: 10% Sheep milk products: 17% Goat milk products: 22% Wool: animal-related wool production, N-coefficients literature-based; Eggs: egg revenues, price (€/100 eggs), N-coefficients literature-based	StoffBilV (2017)
Manure: exported	Derived from the assumption that farms may apply a maximum of 170 kg N/ha/a from organic fertilizers	DüV (2020)
Digestate: exported	Derived from the assumption that farms may apply a maximum of 170 kg N/ha/a from organic fertilizers	DüV (2020)
Seeds, plant material	Implied included by the exported N yield	
Gaseous N losses	Manure: animal-specific standard factors for N emissions from volatilization in animal houses and manure storage, for manure application to the land, and for total N emissions from animal excretions on pasture.	DüV (2020) DüV (2017) StoffBilV (2017)

Parameter	**Implementation in the FADN**	**Note**
Further location, crop and farm characteristics		
Cultivated area	Total utilized agricultural area, excluding fallow land and set-aside land	FADN data considers the different on-farm land allocation on farm-level.
Crop- and yield-specific N demand value	Setting the reference yield against the average farm yield (average of the last five years' yield, excluding very low[1]/high[2] yield); Additions for higher and deductions for lower average yield compared with reference yield (for cereals, grain maize, silage maize, rape, sugar beet, potatoes)	DüV (2020) LfL (2019)
N supply from manure application in previous year	10% of N in organic fertilizer applied, in kg N/ha	DüV (2020)
N supply from soil:		
N available in soil (N_{min})	Utilized arable land: 30 kg N/ha as a standard value	Low estimated value
Humus content	Grassland: 10 kg N/ha as a standard value; Utilized arable land: 0 kg N/ha as a standard value	DüV (2020)
Previous crops, catch crops	Areas with catch crops: 10 kg N/ha as a standard value	DüV (2020)
Crop residues	Vegetables: weighted average according to federal land use proportion	DüV (2020) DESTATIS (2015)

Atmospheric N deposition is reported in an appendix to FarmB according to StoffBilV (2017) and Federal Environmental Agency (2020), but is not part of the assessment and, thus, of the calculated balance.

[1] *According to DüV (2020) Annex 4 Table 3: If the actual crop-specific yield in one of the last five years deviates by more than -20% from the yield of the previous year, it is replaced by the previous year´s yield in determining the difference between forecast yield and reference yield.*

[2] *In order to avoid incorrect data entry: If the actual crop-specific yield in one of the last five years deviates by more than +100% from the average yield at national level, it is replaced by the previous year´s yield in determining the difference between forecast yield and reference yield.*

Table A2: Overview of the total, region-specific and farm type-specific mean indicator values, nitrogen (N) reduction requirements and share of affected farms.

Level		**Indicator**							
		Farm-gate balance (§6 StoffBilV 2017)		Farm-individual balance value (Annex 4 StoffBilV 2017)		Soil surface balance (§8 DüV 2017)		Fertilization planning (§4 DüV 2020)	
		Value[1] kg N/ha	Reduction requirement[2] (share of affected farms) kg N/ha (%)	Value kg N/ha	Reduction requirement (share of affected farms) kg N/ha (%)	Value kg N/ha	Reduction requirement (share of affected farms) kg N/ha (%)	Value kg N/ha	Reduction requirement (share of affected farms) kg N/ha (%)
Total									
Sectoral (n = 6,112)	mean	56	2 (6)	86	15 (30)	25	9 (23)	149	10 (27)
Region[3]									
Northwest (n = 1,951)	mean	73	4 (10)	102	16 (36)	24	10 (27)	159	14 (36)
Central (n = 1,005)	mean	41	1 (2)	81	8 (23)	20	5 (19)	128	7 (23)
South (n = 2,192)	mean	52	2 (5)	88	13 (28)	15	7 (20)	149	9 (25)
East (n = 964)	mean	49	2 (2)	73	16 (31)	35	11 (25)	145	9 (20)
Farm type									
Arable farming (n = 1,551)	mean	18	0 (0)	60	5 (17)	11	4 (14)	160	6 (16)
Dairy farms (n = 1,774)	mean	95	4 (8)	114	19 (34)	25	7 (19)	156	12 (30)
Other cattle and grazing livestock farms (n = 575)	mean	45	2 (5)	100	12 (25)	23	8 (18)	111	6 (22)
Mixed production systems (n = 1,114)	mean	56	1 (5)	80	18 (39)	33	11 (28)	147	10 (27)
Pig and poultry farms (n = 535)	mean	119	12 (21)	112	41 (64)	76	35 (68)	144	28 (58)
Permanent crops (n = 414)	mean	6	0 (0)	56	4 (8)	4	3 (8)	62	10 (30)

[1] *Three-year mean balance values (2016/17 – 2018/19); Fertilization planning = fertilization N demand for a growing season after additions and deductions (2018/19).*

[2] *Quantities related to the total utilized agricultural area of the respective farm type.*

[3] *According to the following federal states classification: Northwest (Schleswig-Holstein, Hamburg, Lower Saxony, Bremen, North Rhine-Westphalia), Central (Hesse, Rhineland-Palatinate, Saarland), South (Baden-Wuerttemberg, Bavaria), East (Mecklenburg-West Pomerania, Brandenburg, Berlin, Saxony-Anhalt, Saxony, Thuringia).*

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4 Evaluation of Nitrogen balances and Nitrogen use efficiencies on farm level of the German agricultural sector (Paper II)

This research article (Paper II) has been revised and re-submitted as:

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In this thesis, the last version of the re-submitted draft is added in the next pages.

Evaluation of Nitrogen balances and Nitrogen use efficiencies on farm level of the German agricultural sector

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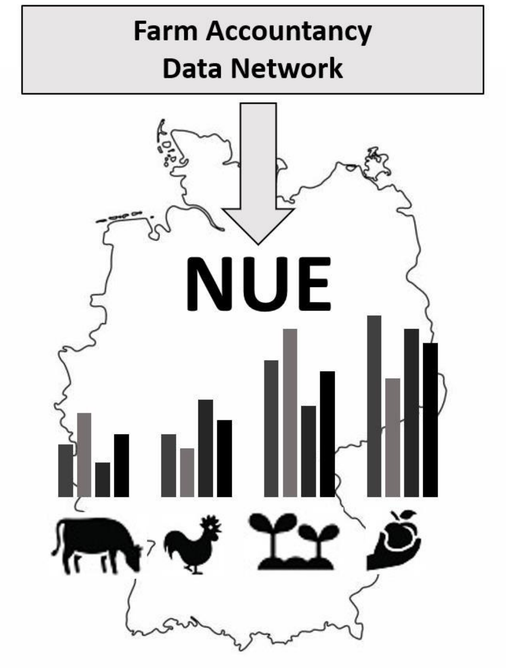
Keywords: N use efficiency, N balance, N indicator, Sustainable intensification, Nutrient policy

Graphical abstract



Highlights

- We calculated the Nitrogen (N) indicators N use efficiency (farm-NUE) and N balance (FarmB) for different farm types using representative farm data from the German Farm Accountancy Data Network.

- We found high variance in N indicators within farm types, indicating efficiency reserves in N use.

- Based on calculated N indicators for 2016/17-2018/19, farms with animals would miss German Sustainable Development Goals for 2030.

- N indicators were interrelated with regional (e.g. altitude), farm structure (e.g. organic manure intensity) and socio-economic (e.g. farm advice) factors.

Abstract

CONTEXT

Use of nitrogen (N), an essential macronutrient, must be optimised in order to ensure food security and food sovereignty, mitigate negative externalities of food production and achieve ambitious (inter-)national environmental, climate and sustainability goals. Nitrogen use efficiency (NUE) is an appropriate indicator for assessing N utilisation on farms.

OBJECTIVE

The aim of the study was to draw general conclusions on N performance of the German agricultural sector, to generate knowledge gain regarding methodological design and estimating N indicators based on farm accounting data, and to increase understanding of interrelations between farm characteristics and N performance in order to support policymakers in finding targeted N mitigation measures.

METHODS

Using data from the German Farm Accountancy Data Network (FADN), we calculated farm-level NUE (farm-NUE) for six farm types (European Union farm typology) covering 5919 farms between the years 2016/17 and 2018/19, considering input and output parameters on farm level, and drew up farm-gate N balances based on national legislation framework. We also developed two explanatory models to identify interrelations between N performance indicators investigated, and regional, socio-economic and farm structural characteristics.

RESULTS AND CONCLUSIONS

The results indicated an increasing trend in NUE from dairy, to pig and poultry, and arable farms, but large variance within each farm type, indicating efficiency reserves in N use. Livestock farms undercut NUE and exceed N surpluses to such an extent that the sustainability goal for 2030 for the national N balance as defined in German Sustainable Development Strategy could be jeopardised. Efficiency reserves of all farm types must be identified and tapped to reach these goals. Multiple regression analysis revealed statistically significant interrelations between N performance and independent variables such as soil fertility, crop selection and diversity, production type, operating profit and consulting services received. Thereby, structural patterns and strategies in order to reduce N waste and increase NUE were identified. However, main source of uncertainty was due to the lack on imported manure amounts from FADN data.

SIGNIFICANCE

Determination of N performance can improve understanding the complexity of agri-environmental interrelations and support policymakers in designing appropriate policies to improve N management.

1 Introduction

1.1 Background

Nitrogen (N) is an essential macronutrient for plant nutrition. Through targeted and needs-based fertilisation and crop rotation, nutrients removed from soil during crop production can be replaced to maintain yields and quality of harvested products and ensure long-term soil fertility. However, once applied to soil, N can react chemically and pass into environmental media as a reactive compound in liquid (e.g. nitrates, nitrites, ammonium), gaseous (e.g. nitrous oxide, ammonia, N oxides) or organic state, affecting the environment in different ways (Winiwarter et al. 2022).

It is important to utilise N in applied fertilisers efficiently for economic reasons in times of volatile prices (DESTATIS 2022a), climate reasons (Zhang & Lassaletta 2022), environmental protection (Schulte-Uebbing et al. 2022), preservation of biodiversity (Dise et al. 2011), protection of human health (Sutton & Bleeker 2013), ensuring food security for a growing world population (Tian et al. 2021) and securing food sovereignty despite fragile global supply chains (Uthes 2022). Reactive N is thus a global concern, resulting in a first ever United Nations resolution on sustainable N management in 2019 (UNEP 2019; Raghuram et al. 2021). In a European Union (EU) context, around 80% of reactive N emissions from all sources to the environment can be attributed to agricultural activities (Westhoek et al. 2015). Thus, use of N in agriculture must become more efficient in order to ensure food security, mitigate negative externalities of food production and achieve ambitious (inter-)national environmental, climate and sustainability goals.

Against this complex background, reference is often made in the scientific community to “sustainable intensification” (Garnett et al. 2013; EUNEP 2015; Quemada et al. 2020), or “ecological intensification” (Cassman 1999; Bommarco et al. 2013; Reinsch et al. 2021). Although there is no unified definition, both concepts are holistic and involve combined improvement of productivity and environmental management of agricultural land. They call for strategies such as integrated crop-livestock production (Rockström et al. 2009; Godfray & Garnett 2014), conservation agriculture, agroforestry, integrated pest management (Godfray & Garnett 2014) and improved N utilisation (EUNEP 2015; Oenema 2015), in order to “sustainalise[1]” agriculture.

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[1] Derived from „sustainability“, describing the process of making something more sustainable by “preserving and/or improving the level of production without degrading natural resources” Eurostat (2013).

The recently announced EU Farm to Fork Strategy for transition to sustainable agriculture addresses efficient N use by proposing two N-related targets for 2030: i) reducing fertiliser use by at least 20% and ii) reducing nutrient losses by at least 50% with maintained productivity (Isermeyer et al. 2020; Barreiro Hurle et al. 2021; Bremmer et al. 2021; European Commission 2022). In a German context, the German Sustainable Development Strategy 2016 (since tightened) (German Federal Government 2021) and the national Climate Action Program 2030 (German Federal Government 2019) are addressing the German N balance, requiring a reduction in the German N balance of around 20 kg N/ha (to an average surplus of 70 kg N/ha) by 2030. In order to maintain productivity levels, this will require a considerable improvement in N utilisation levels.

In this context, the N use efficiency (NUE) is an appropriate indicator for assessing N utilisation in farm systems. It can be derived from N balances and shows the direction of change in N use in food systems at farm, sub-sectoral or sectoral scale, which is crucial for policymakers (EUNEP 2015; Oenema 2015). Both N balance and NUE on farm level provide robust information on N performance and their future relevance as indicators will likely increase due to the growing focus on resource efficiency in current political and societal guidelines.

1.2 Nitrogen performance indicators

Reliable and informative indicators are crucial if managers and policymakers are to take informed decisions and actions (EUNEP 2015). NUE has been identified as a key agri-environmental indicator for assessing the N performance of agricultural systems (Quemada et al. 2020). In general, it is defined as the ratio of N outputs to N inputs and, depending on system boundaries, may be determined on different levels, e.g. for crop production (“field”), animal production (“feed”) or whole farm systems (“farm”) (Powell et al. 2010). This allows hotspots of inefficient N use to be identified on these levels. NUE on farm level (farm-NUE) is a meaningful and inclusive indicator (Oenema 2015), and is based on robust parameters that are also used for estimating farm-gate N balance (FarmB) (equation 1) (Löw et al. 2021b). Another distinctive characteristic of NUE is that a reference value is not required (such as area in *hectares* for nutrient balances), so NUE values are easy to understand and simple to interpret. N balances indicate nutrient pressure from agriculture on the environment so that “*a link between agricultural nutrient use and changes in environmental quality and the sustainable use of soil nutrient resources*” is established (Parris 1998). FarmB and farm-NUE (equation 2) were selected as N indicators in the present study for analysis. However, accurate data on nutrient quantities and qualities of the required parameters are necessary for robust results, and there is a widespread lack of standardised declarations and automatic, software-supported documentation of all on-farm nutrient flows in the German agricultural sector. Further, data access is limited for confidentiality reasons. Therefore, data acquisition can be time-consuming and large datasets are scarce. The Federal Ministry of Food and

Agriculture (BMEL) is working to amend the current respective regulation (StoffBilV 2017), which is expected to significantly improve data availability and accuracy in Germany (Löw et al. 2021a).

$$Farm - gate\ N\ balance\ (FarmB)\ [kg\ N/ha]\ = \frac{Imported\ N\ [kg\ N] - Exported\ N\ [kg\ N]}{Utilized\ agricultural\ area\ [ha]} \qquad \text{(Eq. 1)}$$

$$N\ use\ efficiency_{farm}\ (farm - NUE)[\%] = \frac{Exported\ N\ [kg\ N]}{Imported\ N\ [kg\ N]} \times 100\ [\%] \qquad \text{(Eq. 2)}$$

where: $Exported\ N\ [kg\ N] =$

$$\sum Yield\ of\ marketed\ crops, livestock, animal\ products, organic\ fertiliser, seeds\ and\ plant\ material$$

$$Imported\ N\ [kg\ N] = \sum \begin{matrix} Mineral\ fertiliser, organic\ fertiliser, fodder, livestock, biological\ N\ fixation, (atmospheric\ deposition), \\ seeds\ and\ plant\ material \end{matrix}$$

As no uniform and robust methodology exists at present, (inter-)national findings on NUE are difficult to compare and interpret (Quemada et al. 2020). Different approaches can be adopted, such as (non-)consideration of atmospheric N deposition (ATD) or how biological N fixation (BNF) is valued. Estimation of N content in fodder and manure (Kuka et al. 2019; Klages et al. 2020; Löw et al. 2021b), and inclusion and extent of externalities of upstream (e.g. feed and fodder) and downstream (e.g. animal manure) products are also not harmonised on (inter-)national level (Oenema 2015; Quemada et al. 2020).

Key persons from science, policy and industry communities in Europe have introduced a methodological approach for calculating NUE, a graphical approach to present NUE and defined target values suitable for international benchmarking of agricultural systems (EUNEP 2015). Since different types of farms have specific characteristics, farms need to be categorised and considered separately. The German agricultural sector is highly heterogeneous regarding regional, farm structural and socio-economic characteristics, presumably affecting determining factors for good N performance, as measured by NUE and N balance.

1.3 Research gap

The N balance for the German agricultural sector is currently calculated and reported by the federal Julius Kühn Institute, in collaboration with the Institute of Landscape Ecology and Resource Management, University of Giessen (German Federal Government 2021). The N balance values produced serve as an important benchmark for assessing the progress of Germany towards achieving sustainability goals and are also used for deriving sector NUE. However, efficiency values for different farm types cannot be deduced from these aggregated values. Some studies have analysed N balance and NUE on farm level for different groups of German farm types, e.g. dairy farms in northwest Germany (Scheringer 2002; Kelm et al. 2007; Löw et al. 2020) or scattered throughout Germany (Machmüller & Sundrum 2019; Chmelíková et al. 2021), arable farms (Quemada et al. 2020;

Chmelíková et al. 2021) or pig farms (Schneider et al. 2021). However, sample size is generally rather small, due to the documentation and processing effort required, and comparison of efficiency values is impeded by lack of a uniform and robust methodological approach (EUNEP 2015; Oenema 2015). One study analysed soil surface N balances of the German agricultural sector, with its different farm types, and found interrelations with farm structural and socio-economic variables (Osterburg 2007). A similar study has been conducted in Switzerland (Jan et al. 2017). However, the focus on both studies was on N balances and NUE at *field* level, and not *farm* level. Determinants of N performance indicators on farm level are rarely mentioned in relevant studies in other EU member states, e.g. dairy farms in the Netherlands (Ondersteijn et al. 2003) or in Ireland (Buckley et al. 2016). Thus, there is a knowledge gap regarding N balance (FarmB) and NUE on farm level (farm-NUE) for different farm types in Germany and causal effects of regional, farm structural and socio-economic characteristics. The present study aimed to fill this gap by producing scientific knowledge that can act as a decision support for policymakers designing targeted measures to improve on-farm N performance.

1.4 Objectives and overall research approach

The overall aim of the study was to determine current N balance and NUE on farm level for six main farm types in the German agricultural sector and to identify differences between and within these farm types. Regional, farm structural and socio-economic characteristics were investigated in order to identify interrelations with the selected N performance indicators. Representative farm data were used to draw general conclusions and to increase understanding of N mitigation measures and the ambitious goals set in national and international agricultural, environmental and climate policy (Löw et al. 2021a; BMEL 2022c). A second aim was to address unresolved aspects of methodological design, as a step towards a harmonised approach for deriving N performance indicators on the basis of farm accountancy data. Based on the literature and expert reviews, nine hypotheses (H1-H9) were formulated and tested based on the selected performance indicators (farm-NUE, FarmB):

Regional level

- H1: With increasing soil quality, N performance improves due to better agronomic conditions (Prokopy et al. 2008; Buckley et al. 2016; Amelung et al. 2018).
- H2: With increasing altitude, N performance declines due to poorer agronomic conditions (Jan et al. 2017).
- H3: Large geographic regions (according to soil-climate areas) differ in N performance, with eastern regions showing lower N performance due to limited and variable rainfall during the growing season (Osterburg 2007; Amelung et al. 2018; DWD 2022).

Farm structural level

- H4: The production types differ in N performance, with better performance in organic farming due to limited N input in such systems (Kelm et al. 2007; Jan et al. 2017; Chmelíková et al. 2021).
- H5: Farm types differ in N performance, with pig and poultry farms showing higher FarmB and lower farm-NUE values than other farm types with animals, due to higher ammonia losses (DüV 2020; Amon et al. 2021).
- H6: On farms with large amounts of manure application, N performance is improved by better management and technologies (expert guess).

Socio-economic level

- H7: With increasing farm manager age, N performance improves due to experience (Osterburg 2007; Jan et al. 2017).
- H8: With increasing education level of the farm manager, N performance improves due to better knowledge (Nieberg & Münchhausen 1996; Osterburg 2007; Prokopy et al. 2008).
- H9: With increasing operating profit, N performance improves due to better farm management (Nieberg & Münchhausen 1996; Prokopy et al. 2008).

2 Material and methods

2.1 Data

For the analysis, we used data from the German Farm Accountancy Data Network (FADN), covering around 10,000 farms that are surveyed annually. Sampling is representative for the German agricultural sector, with its different farm types, farm structures and geographic regions, and the FADN provides annual data on financial activities, quantities and socio-economic characteristics (BMEL 2022c).

For calculating farm-NUE, we considered relevant input and output parameters identified previously (Löw et al. 2021b). That study calculated farm-gate N balances for farms as three-year averages (2016/17-2018/19) based on FADN and official documentation and assessment of on-farm nutrient flows (StoffBilV 2017) for six farm types: arable farms, dairy farms, other cattle and grazing livestock farms, mixed production systems, pig and poultry farms, and permanent crop farms. Farms that did not fall into any of these types were removed from the sample in the present study, affecting around 1.5% of the data (Löw et al. 2021a). Mean values were considered for analysis as these are more robust and not as prone to factors such as seasonal weather variability or market fluctuations as annual indicator values. A further adjustment was made regarding the coefficients of feed-N purchases, where due to a reassessment of feed prices during 2009 and 2018 (BMEL 2022a), an inflation effect was neglected compared with Löw et al. (2021b). Thus, inputs increased by approximately 4 kg N/ha at sectoral level compared with the previous study, with a slight increasing effect on FarmB. Based on selection criteria such as continuous participation of farms in FADN over three years, the sample size was 5923 farms. In order to ensure consistency with sectoral data from the national farm survey, farm types were weighted using cluster-specific extrapolation factors (Hansen et al. 2009; Haß et al. 2020).

Based on Löw et al. (2021b), we defined the input and output parameters shown in Table 1.

Table 1. Parameters considered when estimating Nitrogen (N) balance and N use efficiency on farm level and implementation in the methodology used based on German Farm Accountancy Data Network (FADN) data.

Parameter	*Implementation*
Inputs / imports	
Mineral fertiliser	Area-related quantities of nitrogenous mineral fertiliser purchased according to FADN
Organic fertiliser	Import of digestate as a function of revenues from energy crops, divided by prices (FADN) and N coefficients according to StoffBilV (2017), methodically following Löw et al. (2020)
Feed	Animal category-specific expenditure on feed (FADN), feed-specific N cost factors according to Bach (2013).
Livestock	Animal numbers purchased (FADN), animal category and weight-specific N-coefficients according to StoffBilV (2017)
Biological N fixation	Cultivated area of field bean, pea, clover, other legumes according to FADN, crop-specific N-coefficients according to StoffBilV (2017)
Seeds, crop material	Cultivated area of potato, maize, cereal, grain legumes according to FADN, crop-specific N-coefficients according to StoffBilV (2017), amount of seeds according to KTBL (1992)
Outputs / exports	
Yield	Crop-specific revenues and prices according to FADN, crop-specific N-coefficients according to Gamer & Bahrs (2010), Ehrmann (2017), LfL (2019) and DüV (2020)
Livestock	Animal numbers sold or lost (FADN), animal category and weight-specific N-coefficients according to StoffBilV (2017)
Animal products	Including milk, milk products, wool, eggs, N-coefficients according to StoffBilV (2017)
Organic fertiliser	Manure amount of more than 170 kg N/ha transferred to other farms according to DüV (2020), animal category- and management-specific N-excretion rates per head (FADN) according to DüV (2020)
Seeds, crop material	Inferred from the quantities sold

FADN accounting does not cover farm imports of manure, so it was not possible to draw unambiguous conclusions about imported nutrient quantities. The value recorded in monetary accounting for purchased manure cannot be interpreted conclusively, as inter-farm transports depend on many factors (including agricultural structure, feeding management, market structures, prices), and the type and quantity of manure and its nutrient content are not specified.

As ATD is not included in official assessment of farm-gate N balance (StoffBilV 2017), it was not considered as an input parameter. German Environment Agency (2019) quantifies ATD on a region-specific basis, with values between 10 and 15 kg N/ha/yr in most regions. For BNF, only leguminous N fixation on arable land was considered, as BNF on grassland is not part of official reporting.

The main focus in the analysis was on farms with animals, for which FarmB and farm-NUE have higher reliability and accuracy, as usage and export of on-farm organic manure from animals is considered in the data, but not imported organic manure from animals or other manure types (e.g. compost). Farm-gate balances for arable farms and permanent crop farms generally correspond to soil surface N balances (Klages et al. 2017), provided that there is no on-farm biogas plant or livestock production, so estimating FarmB for these farm types would provide limited knowledge, but they were not omitted from the analysis.

2.2 Statistical analysis

Descriptive statistics

We used the equivalent functions in Microsoft Excel Professional Plus 2010 for explorative data analysis and calculated trimmed mean, standard deviation and median for different farm types based on the functions in SAS (SAS 9.4) software (SAS Institute). Trimmed mean is more suitable than arithmetic mean in the case of outliers, skewness or fat tails (Oosterhoff 1994; Wilcox 2017). We used a level of 20% trimming to balance between information loss and robustness (Wilcox 1996). Although loss of power is lower for trimmed mean than for median (Duden & Offermann 2020), we used both location parameters to improve understanding of the data.

Multiple regression analysis

In addition, we performed multiple regression analysis with continuous and dummy variables for non-interval categorised variables (Urban & Mayerl 2018), using detailed information shown in Table A1. For this, we created two explanatory models and specified based on potential determinants of both FarmB and farm-NUE, while generally considering data availability in FADN. First, we developed a baseline explanatory multiple regression model that included internal N flows, which can be regarded as farm structural attributes, as potential determinants explaining the two N performance indicators (FarmB, farm-NUE). Internal N flows are most reflective of N management, so we examined their interrelations with the gross N indicators. For inputs, we considered different types and quantities of organic fertilisers (e.g. pig manure, cattle manure, digestate) and for outputs the N yield of relevant crops and crop groups as continuous determinants. Area-related payments for agri-environment-climate measures (AECM) and production type, split with dummies into organic and conventional farming, were also included in the baseline model. We then developed an advanced explanatory multiple regression model (equation 3) where further determinants of FarmB and farm-NUE were added, grouped into regional, farm structural and socio-economic variables:

$$y = a_0 + a_1 \times x_1 + a_2 \times x_2 + \cdots + a_n \times x_n \qquad \text{(Eq. 3)}$$

where *y* is the command variable, $a_0 \ldots a_n$ are regression coefficients and $x_1 \ldots x_n$ are independent variables

For regional characteristics, dummy variables for natural yield potential based on the German soil fertility indicator *Ertragsmesszahl*, altitude (low, medium, high), and large geographic regions according to a typology based on soil and climate characteristics were tested. Dummy variables for the main regions (North, East, South, West) according to so-called soil-climate areas (Dachbrodt-Saaydeh et al. 2019) could not be derived from FADN, so relevant data were imported from the Thünen Institute database using explicit community codes. Proportion of irrigated area in utilised agricultural area was considered as an additional explanatory variable. Further farm structural characteristics were considered using crop diversity (low, medium, high) as a dummy variable.

For socio-economic variables, school and agricultural education of the farm manager were tested as dummy variables, together with farm size, farmer age, operating profit and consulting services received. Also, received compensation for mandatory environmental requirements in designated areas, expenditure for machinery and external services, and number of employees were considered as continuous variables. A detailed description of the variables investigated can be found in Table A1.

Possible multicollinearity between the independent variables was investigated by correlation analysis with variance inflation factor (VIF), by reviewing tolerance values and by Eigenvalue analysis. If multicollinearity was observed, respective variables were removed (this was done for livestock density, dairy production, and proportion of arable land and grassland).

Estimation procedure

The Ordinary Least Squares (OLS) approach is the conventional way to estimate a regression model, but it was not applied in this study due to the presence of outliers, since the classic OLS estimator of regression models is very sensitive to outliers. Instead, we used the MM-estimator (Finger 2010; Conradt et al. 2017), a robust regression technique with high breakdown value estimation implemented in the “robustreg” estimation procedure in SAS software (version *9.4*).

Thus, two explanatory models were developed for agricultural farms, explaining the N indicators by regional, farm structural and socio-economic variables. Subsamples were developed and analysed for large geographic regions (South, East, West, North), manure N application intensity (farms applying less or more than 50 kg organic N/ha) and farm types (farms with or without animals). The coefficient of determination (R^2) of the models was taken to indicate the proportion of the variance explained for a given probability of error ("goodness of fit"), while the regression coefficients (slope parameter) indicated how strongly the independent variable influenced the dependent variable. The significance of the effect of each independent variable on the dependent variable was assessed by F test at 5% level, based on the null hypothesis, i.e. regression coefficient of zero or no linear relationship between the independent and dependent variable.

3 Results

3.1 Nitrogen balance and Nitrogen use efficiency

FarmB and farm-NUE for representative farms in the FADN as trimmed mean, standard error of the mean (StdMean), and median values are shown in Table 2. Across all farms, trimmed mean value was 56 kg N/ha for FarmB and 64% for farm-NUE. Permanent crop and arable farms showed the lowest FarmB and highest farm-NUE, with considerable differences from farm types with animals. For arable farms, FarmB was 13 kg N/ha and farm-NUE was 99%, while for permanent crop farms the corresponding values were 1 kg N/ha and 123%. For farm types involving animals, FarmB decreased from pig and poultry farms (135 kg N/ha) to dairy farms (93 kg N/ha), mixed production systems (62 kg N/ha), and other cattle and grazing livestock farms (50 kg N/ha). For farm-NUE, the order of increase was dairy farms (44%), pig and poultry farms (53%), other cattle and grazing livestock farms (59%), and mixed production systems (63%) (Table 2). An additional analysis only for animal farms revealed farm-NUE of 52% (0.4 StdMean) and FarmB of 84 kg N/ha (1.2 StdMean), while for farms without animals farm-NUE was 101% (1.6 StdMean) and FarmB was 10 kg N/ha (0.9 StdMean). Organic farming showed slightly higher farm-NUE (72%) and lower FarmB (21 kg N/ha) than conventional farming (64% and 60 kg N/ha, respectively). Comparing the regions investigated, South and East showed better mean N performance than West and North. For organic fertiliser production, higher efficiency and lower surplus values were related to farms with lower production, with an improving trend in N performance from low to high manure N production.

Table 2. Nitrogen use efficiency and Nitrogen balances on farm level for all farms and farm types investigated.

Scale type	**Sample size (n)**	**Indicator**					
		Farm N balance (kg N/ha)			**farm-NUE (%)**		
		Trimmed mean	StdMean	Median	Trimmed mean	StdMean	Median
All	5919	56	1.012	44	64	0.553	64
Farm type							
Arable	1518	13	1.259	7	99	1.451	100
Dairy	1744	93	1.626	82	44	0.455	45
Other cattle	570	50	3.243	24	59	2.555	62
Pig, poultry	541	135	3.067	130	53	0.900	55
Permanent	410	1	1.306	4	123	10.916	95
Mixed	1136	62	1.784	53	63	0.872	64
Production type							
Organic	505	21	2.028	19	72	5.046	61
Conventional	5414	60	1.072	49	64	0.547	65
Region							
South	2088	42	1.586	32	69	1.144	67
East	896	49	2.197	44	63	1.521	59
West	1561	70	2.216	50	62	0.989	66
North	1374	69	2.069	66	62	0.899	61
Organic fertiliser production[1]							
0-40 kg Norg/ha	2282	12	0.923	8	99	1.585	97
40-120 kg Norg/ha	1628	57	1.327	45	56	0.749	58
>120 kg Norg/ha	2009	121	1.513	111	47	0.432	47

[1]Accumulated quantities of manure and plant-based digestate, no consideration of gaseous N losses from volatilisation in stables and storage (gross).

Comparison of N inputs and N outputs means by farm type are presented in Table 3. N inputs were lowest for permanent crop farms (46 kg N/ha) and other cattle and grazing livestock farms (103 kg N/ha), followed by arable farms (121 kg N/ha), mixed farms (158 kg N/ha), dairy farms (166 kg N/ha), and were the largest for pig and poultry farms (344 kg N/ha). Regarding N outputs, mean values were lowest for permanent farms (31 kg N/ha) and highest for pig and poultry farms (164 kg N/ha). Variations were greatest for pig and poultry farms, 25% (Q1) and 75% (Q3) quartiles varied between 108 and 248 kg N/ha.

Table 3. Accumulated N input and N output parameters considered for calculating investigated N indicators on farm level.

Scale type	**Sample size (n)**	**N inputs (kg N/ha)**				**N outputs (kg N/ha)**			
		Mean	Median	Q1	Q3	Mean	Median	Q1	Q3
All	5919	152	133	68	198	102	83	44	126
Farm type									
Arable	1518	121	123	77	160	121	119	90	144
Dairy	1744	166	150	88	218	78	60	41	90
Other cattle	570	103	81	24	161	66	42	14	89
Pig, poultry	541	344	298	236	391	208	164	108	248
Permanent	410	46	34	13	57	31	25	23	27
Mixed	1136	158	142	84	200	123	90	60	121

Q1 and Q3 represent the 25% and 75% quartiles of the sample.

FarmB and farm-NUE for farm types with animals are shown as boxplots (10th to 90th percentile) in Figure 1. For FarmB, pig and poultry farms (130 kg N/ha; median surplus) had considerably higher surpluses than the other farm types but the variation was consistently large within all farm types. For farm-NUE, the median values were similar for all farm types with animals, but highest for mixed production systems (64%) and lowest for dairy farms (45%). There was again considerable variation in these values, with rather small ranges within dairy farms and pig and poultry farms compared with other cattle and grazing livestock farms and mixed production systems.

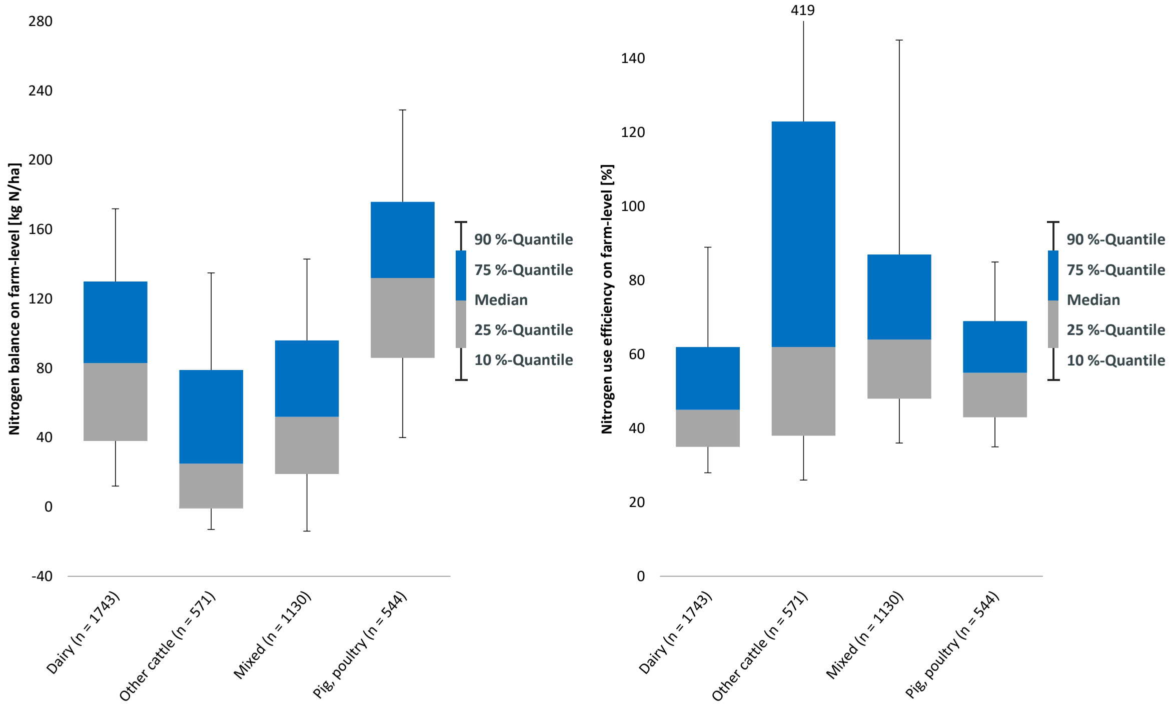

Figure 1. (Left) Nitrogen balance (FarmB) and (right) Nitrogen use efficiency (farm-NUE) on farm level as three-year means (2016/17-2018/19) for farms with animals in the dataset.

As shown in Figure 1, FarmB and farm-NUE did not always go hand in hand. To better highlight the relationship, these indicators are displayed on two axes in Figure 2 for farm types with animals. As mentioned, the sample contained many outliers, so for better visualisation the x-axis (FarmB) was trimmed at -60 and 380 kg N/ha, and the y-axis (farm-NUE) at 260%, taking into account that the sample size decreased by 3.5%. The total sample of 3962 farms with animals was reduced to 3823, due to missing values or lack of compatibility with defined axes. The majority of animal farms retained were densely distributed between a maximum of FarmB = 200 kg N/ha and farm-NUE = 80%. For pig and poultry farms (R^2 = 0.38) and dairy farms (R^2 = 0.24), the distribution cloud was more right-leaning, while for mixed production systems (R^2 = 0.25) and other cattle and grazing livestock farms (R^2 = 0.21) it seemed to be more left-heavy. For dairy farms and pig and poultry farms, the distribution was more homogeneous than for the other farm types (Figure 2).

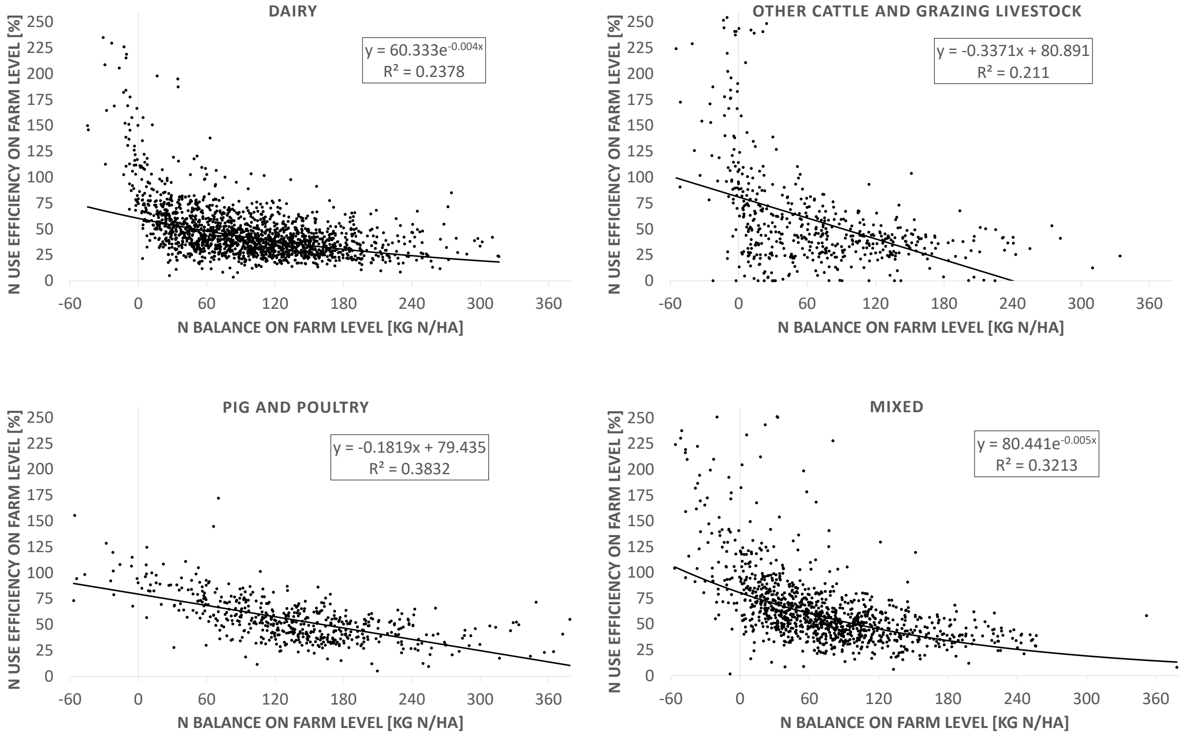

Figure 2. Nitrogen use efficiency on farm level (farm-NUE) in relation to Nitrogen balance on farm level (FarmB) and farm type as three-year means (2016/17-2018/19) for farms with animals in the trimmed dataset (n = 3823).

3.2 Regression analysis

Table 4 shows estimated values of the selected regression model variables (see section 2.2). In baseline regression, goodness of fit was highest for the model explaining FarmB surplus (R^2 = 0.40), while the value was R^2 = 0.43 for the advanced multiple regression model. Goodness of fit was considerably lower for the models explaining farm-NUE (R^2 = 0.19 and 0.20 in baseline and advanced regression, respectively). This pattern was also observed for the subsamples, with the highest goodness of fit observed for the West region (R^2 = 0.45 for FarmB, R^2 = 0.24 for farm-NUE). Goodness of fit was generally higher for subsamples with comparatively higher manure intensity. The regression results for different variables are described in detail below.

Farm structural interrelations

Focusing on organic manure quantities in kg N per hectare in baseline regression model (Table 4), coherent[2] and significant results were identified for all types of manure. The strongest effect on farm-NUE was found for other animal manure and cattle manure (-0.4%, $p<0.01$). The effect of an increase of 1 kg N/ha in organic manure on FarmB ranged from 0.5 to 1.6 kg N/ha in the different regions, while the effect on farm-NUE ranged from -0.1 to -0.6 %. In an additional analysis, we grouped the farms

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[2] In this context, “coherent“ means a reciprocal interplay between an increasing indicator value for FarmB and a decreasing indicator value for farm-NUE.

according to cattle and pig manure application intensity into three dummy variables: low (0-40 kg N/ha), medium (>40-120 kg N/ha) and high (>120 kg N/ha) (see Tables A3 and A4). For both cattle and pig manure, the results were coherent and significant, with each unit increase in intensity of manure application having a decreasing effect on farm-NUE. For cattle manure, the increasing effect on FarmB was greatest for high manure application intensity (+1 kg N/ha), while the decreasing effect on farm-NUE was greatest for medium-intensity application (-0.4%). Overall, the coefficients varied only slightly. For pig manure, low manure application intensity had the greatest effect in both increasing FarmB (+1.1 kg N/ha) and decreasing farm-NUE (-0.4%).

On comparing N yield of relevant crops and crop groups in kg N per hectare, a decreasing effect on FarmB was observed for grassland, sugar beet, maize (all -0.4 kg N/ha, $p<0.01$) and wheat (-0.1 kg N/ha, $p=0.02$), while a positive effect was found for rapeseed yield whereby 1 additional kg N/ha yield increased FarmB by 0.4 kg N/ha ($p<0.01$). Higher N yields had an increasing effect on farm-NUE for all crops and crop groups except winter grain yield in South region (not significant). The positive effect was greatest for sugar beet yield, with 1 additional kg N/ha yield increasing farm-NUE by 0.5% ($p<0.01$), and smallest for winter grain yield (+0.2%, $p<0.01$). For vegetables and other crops, the arable area-related ratio (hectares per hectare) was considered. For vegetables, the results were non-coherent and only significant for farm-NUE (+14%, $p=0.04$). For other crops, the results were coherent and significant. The effect on farm-NUE was 8.4% ($p<0.01$), so that a 10% increase in cultivated area was associated with an 0.8% increase in farm-NUE.

In terms of production type, organic farming showed a decreasing effect on FarmB (-26.1 kg N/ha) compared with conventional farming. A significant decreasing effect was also observed for the different regions, where it was highest in North (-39.4 kg N/ha) and lowest in East (-17.4 kg N/ha).

Taking further determinants of the advanced regression model into consideration and focusing on crop diversity, the results were coherent and significant (see Table 5 for an overview and Table A2 for comprehensive results). Nitrogen performance was best for low crop diversity, with the greatest effect in increasing farm-NUE (+2.8%, $p=0.01$) compared with high diversity, while medium crop diversity was intermediate. Significant interrelations between low crop diversity and decreasing FarmB were also observed for different organic N fertiliser input systems and farms with animals. In an additional analysis focusing only on farms with more than 70% arable land, similar results were obtained.

The direction of significant effects was mainly coherent among the regions and farm systems investigated, but the level varied widely. This was observed for different manure types, which had a coherent increasing effect on FarmB and decreasing effect on farm-NUE. A significant decreasing effect only on FarmB was identified for organic farming (highest for North), while spring grain showed an increasing effect only on farm-NUE (highest for East). Rapeseed and winter wheat yield in high manure application intensity systems showed an increasing effect on both FarmB and farm-NUE. For vegetable area and other crop area, indistinct effects were observed among the subsamples, while the direction and level of the effect varied within regions and farm types. For detailed results, see Tables 4 and 5.

Regional interrelations

The geographic region in which farms were located influenced FarmB and farm-NUE. Farms located in the South and East regions had significantly higher farm-NUE (+3.7%, p<0.01) than farms in North (+2.7%, p=0.02). For farms located in the West region, no statistically significant results were observed. For low organic N input systems, the effect on FarmB was highest in the East region (-11.6 kg N/ha), while for high organic input systems the effect was highest in South (-12.9 kg N/ha). Thus, East farms with low organic inputs, and farms in South with high organic inputs, showed lower N surplus than farms in other regions. Soil quality, indicated by natural yield potential and represented by three dummy variables, did not affect FarmB and farm-NUE significantly. Altitude had significant results on FarmB and farm-NUE. Medium altitude had the strongest decreasing effect on farm-NUE (-9.3%, p<0.01) compared with high, the altitude level positively effecting N performance most. The effect of low altitude was also significant, but more moderate, for both FarmB and farm-NUE. Similar results were found for high organic N input systems and farm types with animals. For increasing irrigated area, no significant results were observed.

Socio-economic interrelations

The effect of total farm size in hectares as a categorical variable was coherent, with the greatest increasing effect on farm-NUE (+4.9%, p<0.01) for small farms. These significant and coherent results were also observed for low and high organic N input systems and for different farm types, whereas for farms with animals the effect was only significant for farm-NUE (+4.5%). Significant results were not observed for farm manager´s age, except that for low organic N input systems, younger age was linked to higher FarmB (+6.4 kg N/ha) and lower farm-NUE (-9.5%). Medium school education had the strongest effect on farm-NUE (+3.1%, p=0.01). Similarly, medium agricultural education had a decreasing effect on FarmB (-3.5 kg N/ha) compared with high agricultural education. For increasing operating profit in €/ha as a categorical variable, high operating profits were interrelated with lower FarmB and higher farm-NUE, and thus the decreasing effect on farm-NUE was highest for low operating profit (-7.2%, p<0.01). Low use of consulting services was interrelated with decreased farm-NUE (-1.5%, p=0.04). An increase in payments received for AECM in €/ha caused a significant decrease in FarmB (-0.03 kg N/ha), but had no significant effect on farm-NUE. Compensation received for mandatory environmental requirements in designated areas and costs for machinery and external services did not affect the dependent variables investigated, but number of employees slightly increased FarmB (0.1 kg N/ha, p=0.04).

No correlation issues or extreme Eigenvalues were observed following the criteria reported in Schreiber-Gregory (2017). VIF of all independent variables in both models was clearly lower than 10, and tolerance values were higher than 0.1.

Table 4. Specification and results of the baseline multiple regression model for Nitrogen balance (FarmB) and Nitrogen use efficiency (farm-NUE) on farm level (n = 5923).

Independent variables	**Description**	**Unit**	**Dependent variables**		**Scale type**							
			All farms		***Regions***							
					South		***East***		***West***		***North***	
			N balance (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)
			Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
Organic manure - cattle		kg N/ha	1.0*	-0.4*	1.1*	-0.5*	1.1*	-0.4*	1.1*	-0.3*	0.8*	-0.3*
Organic manure - pig		kg N/ha	0.8*	-0.2*	0.7*	-0.2*	0.7*	-0.2*	0.9*	-0.2*	0.7*	-0.1*
Organic manure - poultry		kg N/ha	1.1*	-0.2*	1.1*	-0.2*	1.6*	-0.2*	1.0*	-0.2*	1.2*	-0.1*
Organic manure - other animals		kg N/ha	0.5*	-0.4*	0.8*	-0.6*	0.8*	-0.4*	0.6*	-0.4*	0.0	-0.2*
Organic manure - digestate		kg N/ha	0.6*	-0.2*	0.9*	-0.3*	0.1	0.3	1.0*	-0.2*	0.5*	-0.1*
Wheat yield		kg N/ha	-0.1*	0.3*	-0.2*	0.3*	-0.2	0.5*	0.0	0.2*	0.0	0.2*
Rye yield		kg N/ha	0.2	0.3*	0.9*	0.0	0.5	0.2	-0.1	0.3*	-0.2	0.3*
Winter grain yield		kg N/ha	0.0	0.2*	0.2*	-0.1	0.1	0.3*	-0.3*	0.3*	-0.2*	0.3*
Spring grain yield		kg N/ha	0.0	0.2*	0.2	0.2*	-0.1	0.3*	-0.4*	0.2*	0.0	0.1*
Maize yield		kg N/ha	-0.4*	0.4*	-0.4*	0.3*	-0.1	0.2*	-0.7*	0.5*	-0.4*	0.3*
Rapeseed yield		kg N/ha	0.4*	0.2*	0.1	0.2	0.5*	0.2	0.3	0.3*	0.4*	0.2*
Sugar beet yield		kg N/ha	-0.4*	0.5*	-0.4*	0.4*	-1.8*	1.0*	-0.3	0.5*	-0.5*	0.6*
Potato yield		kg N/ha	0.0	0.3*	0.3	0.2	0.8	0.0	-0.3*	0.4*	0.1	0.3*
Grassland yield		kg N/ha	-0.4*	0.2*	-0.6*	0.3*	-0.7*	0.3*	-0.3*	0.2*	-0.1*	0.2*
Vegetable area (factor)		ha/ha	13.1	14.0*	22.4	-27.0*	-95.7*	-29.3	13.0	30.1*	-104.2*	35.1
Grain legumes yield		kg N/ha	0.2	0.1	0.1	0.3	0.9*	-0.3	0.0	0.1	-0.3	0.3*
Other crops area (factor)		ha/ha	-10.8*	8.4*	-5.7	-5.5	-17.5	49.5*	-17.9	-17.2*	-22.0*	22.9*
Production type	organic	0: no; 1: yes	-26.1*	1.2	-18.9*	-3.4	-17.4*	0.1	-35.4*	4.9	-39.4*	-0.4
	conventional	0: no; 1: yes										
Payments for AECM[1]		€/ha	-0.05*	0.01*	-0.01	-0.01	-0.04	0.02	-0.08*	0.03*	-0.06*	0.01
Observations		n	5923	5923	2088	2088	896	896	1561	1561	1376	1376
Goodness of fit		R^2	0.40	0.19	0.38	0.14	0.36	0.21	0.45	0.24	0.43	0.30

Regression coefficients are shown in a way that positive values are to be understood as an increase of the indicator, negative values as a decrease.

[1] Payments received for agri-environment-climate measures, not including payments for ecological farming and payments for compensations.

**Significant regression coefficients (p-value < 0.05).*

Table 5. Specification and results for selected regional and socio-economic variables of the advanced multiple regression model for Nitrogen balance (FarmB) and Nitrogen use efficiency (farm-NUE) on farm level (n = 5923).

Independent variables	**Description**	**Unit**	**Dependent variables**		**Scale type**							
			All		***Organic N application***				***Farm type***			
					< 50 kg N/ha		***> 50 kg N/ha***		***Arable, permanent***		***Animals, mixed***	
			N balance (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)
			Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
Region												
Large geographic regions	South	0: no; 1: yes	-7.3*	3.7*	-5.1	3.0	-12.9*	1.2	-5.0	2.6	-9.9*	2.3*
	East	0: no; 1: yes	-9.2*	2.7*	-11.6*	10.9*	-8.7*	-1.3	-13.4*	11.0*	-8.1	-0.1
	West	0: no; 1: yes	0.4	0.4	-6.2*	5.9*	0.7	-1.3	-5.7	3.5	1.4	-0.5
	North	0: no; 1: yes										
Altitude	low	0: no; 1: yes	15.5*	-4.5*	0.9	-6.4	9.1*	-4.1*	3.1	4.9	10.2*	-4.2*
	medium	0: no; 1: yes	18.7*	-9.3*	3.2	-7.3	15.6*	-7.2*	2.9	6.2	15.6*	-7.6*
	high	0: no; 1: yes										
Socio-economic												
Farm size	low	0: no; 1: yes	-8.6*	4.9*	-9.0*	9.4*	-8.3*	4.4*	-13.4*	11.2*	-4.4	4.5*
	medium	0: no; 1: yes	-2.5	1.0	-5.1*	3.1	-3.1	0.6	-9.4*	6.3*	0.3	0.5
	high	0: no; 1: yes										
Age	low	0: no; 1: yes	3.0	-2.2	6.4*	-9.5*	-0.6	0.6	3.2	-5.6	1.7	0.1
	medium	0: no; 1: yes	1.3	-1.1	0.5	-1.4	1.8	-0.4	1.1	-0.4	1.3	-0.2
	high	0: no; 1: yes										
School education	low	0: no; 1: yes	-2.5	1.4	-3.7	2.4	-2.9	0.1	-2.3	0.4	-4.3	1.2
	medium	0: no; 1: yes	-5.6*	3.1*	-5.9*	3.5	-7.9*	0.8	-4.0	0.6	-8.4*	2.5*
	high	0: no; 1: yes										
Agricultural education	low	0: no; 1: yes	-2.2	1.0	-1.2	-0.1	-4.2	-0.9	1.3	-0.6	-4.0	-0.3
	medium	0: no; 1: yes	-3.5*	0.3	2.6	-3.4	-7.9*	0.5	2.8	-3.6	-7.1*	0.4
	high	0: no; 1: yes										
Operating profit	low	0: no; 1: yes	10.6*	-7.2*	3.3	0.6	14.5*	-7.5*	8.8*	-2.6	10.9*	-7.3*
	medium	0: no; 1: yes	4.9*	-5.0*	-1.8	4.9	8.3*	-4.8*	1.9	2.5	6.4*	-5.2*
	high	0: no; 1: yes										
Consulting services	low	0: no; 1: yes	9.7*	-1.5*	2.8	-0.8	14.0*	-1.3	-0.1	2.5	13.8*	-1.6*
	high	0: no; 1: yes										
Payments for AECM[1]		€/ha	-0.03*	0.01	-0.02	0.00	-0.03*	0.00	-0.02	-0.01	-0.03*	0.00
Number of employees		heads	0.12*	-0.05	0.12*	-0.13*	0.12	0.06	0.10	-0.11	0.24	0.04
Observations		n	5923	5923	2471	2471	3452	3452	1932	1932	3991	3991

Goodness of fit	R^2	0.43	0.20	0.19	0.09	0.33	0.22	0.18	0.06	0.37	0.17

Regression coefficients are shown in a way that positive values are to be understood as an increase of the indicator, negative values as a decrease. Full results of advanced multiple regression analysis can be found in the Appendix.

[1] *Payments received for agri-environment-climate measures, not including payments for ecological farming and payments for compensations.*

**Significant regression coefficients (p-value < 0.05).*

4 Discussion

4.1. Main findings

Nitrogen balance and N use efficiency

The results obtained for farms in the dataset are representative for the agricultural sector in Germany (BMEL 2018), and hence not directly comparable with other international studies, which are often conducted on a smaller scale and possibly have an element of self-selection in recruiting farmers. In fact, the validity of comparing results across individual studies is subject to uncertainty around the methodological approach applied. Thus, we refrain from comparing the indicator values of selected case studies, but do so when discussing the regression analysis.

The German Sustainable Development Strategy and Climate Action Program 2030 addressing the German N balance set a mean national FarmB target of 70 kg N/ha by 2030 (German Federal Government 2019, 2021). Considering the respective data basis used in federal and university research, this equates to sector-level farm-NUE of at least 60% (German Federal Government 2021). The EU Nitrogen Expert Panel has set rough farm-NUE target values of up to 60% for mixed crop-livestock systems, depending on factors such as livestock density, and up to 90% for farms without animals (EUNEP 2015). The values obtained in the present study (FarmB 56 kg N/ha, farm-NUE slightly over 60% for all German farms) might lead to the conclusion that national N management is already in line with sustainability goals and that further efforts are unnecessary. This is by no means the case, as several main aspects need to be considered:

(1) Our calculations were for relevant parameters according to StoffBilV (2017), the official regulation on recording and assessing farm-gate balances. Thus, selection of parameters on farm level was not in line with the data basis used for calculating sector N balances in national sustainability reports and relevant parameters for most accurate representation (detailed site- and crop-specific BNF or site-specific ATD) were not included (Löw et al. 2021a; Löw et al. 2021b). Here, BNF on grassland may be a considerable underestimated N input for other cattle and grazing livestock farms (Nimmo et al. 2013; Godinot et al. 2015). We considered BNF for other cattle and grazing livestock farms and ATD for pig and poultry farms according to mineral fertiliser intensity and livestock density in a subanalysis. These additional N inputs decreased farm-NUE for other cattle farms (-2%) and pig and poultry farms (-3%) slightly, with NUE on sectoral level remaining constant (see Table A5).

(2) Purchased quantities of organic fertilisers were underestimated because FADN provides insufficient information on trade in organic fertilisers, in terms of quantities and type (e.g. manure or compost) (Löw et al. 2021b). Focused redevelopment of FADN into a Farm Sustainability Data Network within the EU Farm to Fork strategy could rectify this, but would require farm-level data on the environment

and social farming practices to be collected prospectively (Barreiro Hurle et al. 2021; European Commission 2021). To our knowledge, there is currently no sophisticated approach for estimating manure transport, as trade patterns are very heterogeneous due to differences in agricultural structure in Germany and Europe. Imported organic fertilisers have high relevance not only for arable and permanent crop farms, but also for farms with animals, as shown by a previous evaluation of national farm survey data (Löw et al. 2021a). Thus, it is difficult to assess farm-NUE for farms without animals in relation to the target value of 90% for these farm types (EUNEP 2015; de Vries & Schulte-Uebbing 2020).

(3) Farms with animals (dairy farms, other cattle and grazing livestock farms, pig and poultry farms) showed a farm-NUE of 52% and N surpluses on a level that the sectoral sustainability goal for 2030 could be jeopardised (EUNEP 2015; German Federal Government 2021). Also, the relatively high sectoral farm-NUE was masked by the positive results for other farm types (e.g. permanent crop farms), leading to an increase in farm-NUE for all farms.

(4) The FarmB and farm-NUE boxplots (Figure 1) revealed broad ranges of N indicator values for farms with animals. Even if mean farm-NUE of the respective farm types had been good (it was not in most cases), this indicates a need for further efforts. The goal must be to ensure that the majority of farms become more efficient, as environmental issues relating to N, such as eutrophication, air pollution or nitrate pollution, are often site-specific and concentrated to small regional scale (Sutton & Bleeker 2013; de Vries & Schulte-Uebbing 2020; Schulte-Uebbing et al. 2022). Our results also showed potential for efficiency improvements within each farm type.

(5) For our main analysis, effects of externalities were not considered. In a recent study, Quemada et al. (2020) investigated the effect of externalised N inputs on NUE for farms in EU countries. By considering N losses for production of purchased feed, farm-NUE decreased by up to 15%, depending on farm type and country. In this study, we conducted a subanalysis considering externalities with different efficiency levels for purchased feed and sold manure (see Table A6). According to their occurrence and magnitude, we found that both factors can have a serious impact. If external systems reach a high NUE, sectoral farm-NUE stands out with 51% while it is 43% for less efficient systems. Our main results are supported by this aspect, revealing the existence of methodological refinements and the importance of defining judicious system boundaries.

(6) Taking these points into account, one can be critical of the N performance indicator values. Slight exceedance of the target value does not mean that no further effort is needed. Instead, urgent efforts on farm level are needed to achieve the sustainability goals defined on different temporal and spatial scales and for different environmental media. Methodological advances in the outlined approach are needed in order to describe farm-gate N flows more precisely.

Determinants and hypothesis testing

We investigated the effect of several regional, farm structural and socio-economic variables on FarmB and farm-NUE using MM-estimator, a robust regression technique. In addition to the analysis for all farms, we also differentiated according to region, organic N fertiliser application intensity, and farm types with and without animals. When comparing our regression results with those of others, e.g. Jan et al. (2017), Buckley et al. (2016) or Osterburg (2007), it is important to consider the differences between studies in (i) the N balance approach and NUE level used, (ii) the type of farms investigated and (iii) the econometric approach and model specification used for the determinant analysis. Accordingly, few studies are comparable.

Farm structural interrelations

Among farm structural interrelations, organic farming was associated with better N performance than conventional farming, supporting hypothesis H4. This may be due to the substantially lower N intensity in organic production, both for mineral (prohibited) and organic fertilisers. Further research is needed to identify farm type-specific implications. Several case studies in Germany have also found lower N surpluses and higher N efficiencies for organic production types also under consideration of grassland BNF (Kelm et al. 2007; Chmelíková et al. 2021).

For farm types with animals, pig and poultry farms were associated with the highest FarmB and also lower farm-NUE than mixed production systems and other cattle and grazing livestock farms, due to their higher N intensity with respect to mineral fertilisers and purchased feedstuffs, in agreement with previous findings (Jan et al. 2017). Mean indicator values were best for mixed production systems, mostly arable with pigs or cattle. These farms produce much of their animal feed themselves and thus have a high degree of self-sufficiency. Regression analysis showed the lowest effect in reducing farm-NUE for pig manure, compared with other manure types, supporting hypothesis H5.

Interestingly, all manure types showed a decreasing effect on farm-NUE, which was lowest for manure from pig and poultry. A previous study found that manure from pig and poultry is associated with lower soil surface N balance than manure from cattle and other animals (Osterburg 2007). We also observed that increased pig manure application intensity was interrelated with higher farm-NUE compared to lower intensities, supporting hypothesis H6, at least for farms using pig manure. This positive link between high manure application intensity and high N efficiency is a counterintuitive result, based on accurate farm data and a large sample size (Löw et al. 2021b), however, it can be explained by more efficient manure management in specialised, intensive pig farms. Anyhow, even with a higher farm-NUE, N surplus might be higher in these farms due to higher livestock densities. Also Nieberg & Münchhausen (1996) found that increased animal manure application leads to higher soil surface N surpluses. As high application intensity was interrelated with the highest increase in FarmB for cattle manure, it appears that intensification of dairy production is accompanied by rising N surplus. Several studies report similar links (Osterburg 2007; Gourley et al. 2012; Buckley et al. 2016), with associated risks of N losses to the environment throughout the production cycle (e.g. grazing, manure management, feedstuff storage) (Löw et al. 2020).

Grain legume N yield had a significant effect in increasing FarmB only in East region, probably because the number and size of arable farms with potential grain legume cultivation is highest in that region (Haß et al. 2020). Obviously, farmers do not fully account N from BNF towards crop nutrient needs, so that higher levels of BNF lead to increased FarmB.

Maize, sugar beet and grassland yield were associated with the largest decreasing effect on FarmB, while it was maize and sugar beet yield with the largest increasing effect on farm-NUE. These crops can all obtain a good N supply from organic fertilisers and can extract relatively high amounts of N from the soil N pool. Maize and grassland produce N-rich biomass. Osterburg (2007) also observed that maize and grassland had the largest effect in lowering N balance and that rapeseed had the smallest effect, even increasing N balance in some cases. Likewise, we found an increasing effect of rapeseed yield on FarmB. However, the effects of grain N yield on N performance were less distinct and varied with region. Winter grain and spring grain gave less improvement in farm-NUE, whereas higher coefficients were obtained for rye and wheat, indicating better N utilisation. Interestingly, farms with low crop diversity were associated with significantly better N performance, possibly owing to their highly specialised technical equipment and management activities.

Regional interrelations

An increase in natural yield potential did not have a significant effect on the N indicators investigated, either for all farms or for different organic N application intensities or farm types. Therefore, there was no support for the hypothesis (H1) that with increasing soil quality (including soil genesis, state and type), N performance improves due to better agronomic conditions, e.g. soil aeration and temperature, soil infiltration, or cation-exchange capacity, which causes better N utilisation and therefore lower risks of N losses (Amelung et al. 2018). Buckley et al. (2016) found significant effects whereby farms with good land use potential had higher NUE values than farm groups with average and poor land use potential. Greater adoption of best management practices on farms with higher soil quality has also been observed in other studies (e.g. Prokopy et al. 2008). Jan et al. (2017) found significantly lower N efficiencies of Swiss mountain farms than farms in the plains region. In contrast, in the present study we found a significant effect for altitude, with the lowest FarmB and highest farm-NUE for farms located above 600 m, followed by low altitude (0-300 m) and medium level (300-600 m). Thus, farms located in high-altitude regions were associated with lower N surplus, owing to lower N intensity and higher farm-NUE, indicating relatively high N yield potential in the German mountain regions, e.g. due to a higher share of grassland. This link, which was apparent for farms with livestock, can also be explained by more extensive, grassland-based cattle farms in higher altitudes. Hence H2 was not supported.

Farms in the South and East were associated with lower FarmB and higher farm-NUE than farms located in the West and North, so the results did not support H3. Similarly, Osterburg (2007) found the largest positive effect on N performance in the South region and the smallest in North. In the East region, this may be attributable to the relatively high proportion of arable land, which tends to have good N efficiency, although the soils are often sandy and grain yields are relatively low. Lower manure application intensity due to low regional livestock densities may also be decisive (Zinnbauer et al. 2023). The South region has favourable soil and climate conditions (Amelung et al. 2018), and relatively well-balanced regional livestock density (Zinnbauer et al. 2023). Moreover, Bavaria and Baden-Württemberg, which principally define the South region, have long-standing and well-managed water protection advisory services (Ebert et al. 2018), optimised grassland management (LfL 2022) and targeted cooperative action programmes (STMELF & STMUV 2022). The four large geographic regions of Germany are clusters with similar soil and climate patterns, based on so-called soil climate-areas, whereas 50 areas are classified according to soil (e.g. soil type) and weather (e.g. long-term precipitation) parameters. A neighbourhood distributed cluster system is widely applied in agri-environmental science, e.g. by federal research institutions within the scope of BMEL (Dachbrodt-Saaydeh et al. 2019; Duden et al. 2019; Schmitt et al. 2022).

Socio-economic interrelations

In addition to characteristics of the region and farm structure, socio-economic characteristics were shown to be crucial. Counterintuitively, small farm size (up to 50 ha) was found to have a positive effect on N performance, reducing FarmB and increasing farm-NUE compared with large farm size (>180 ha). Similar findings were made for farms with different organic application intensities or farms without livestock. This agrees with some previous findings (Buckley et al. 2016), but the effect of farm size on N performance is a recurring theme in the literature, with inconsistent results (Nieberg & Münchhausen 1996; Buckley et al. 2016; Jan et al. 2017). For farmers age, significant results were found only for the subsample of farms with low organic N application intensity, where a decreasing effect on N performance was observed for the young age group. Surprisingly, the lowest N surplus was associated with medium farmer education level, both for school and agricultural education. It seems that younger or better-educated farm managers aim at maximising output, leading to higher N intensity and thus to higher FarmB. The experience of the farm manager seemed to play a greater role for N performance than more recent or more comprehensive education in systems with low organic N application intensity. These results tentatively support H7 and agree with findings by Osterburg (2007) and Jan et al. (2017), but do not support H8. Increasing operating profit proved to be associated with significantly better N performance, supporting H9, which may be a consequence of optimised technical and management equipment as a positive interrelation between high capital expenditure and improved nutrient management has been reported (Prokopy et al. 2008). In order to explore this in more detail, costs for machinery and external services were considered, but did not show significant results. Compensation for mandatory environmental requirements in designated areas also had no significant effect, but we observed positive effects of AECM payments on N surplus, with +1,000 €/ha for AECM reducing FarmB by -28 kg N/ha. This is not surprising, as such measures exist in order to (financially) promote AECM and associated positive ecosystem services.

The regression models were characterised by moderate to low goodness of fit values of a similar magnitude as in other studies (Jan et al. 2017). Possible explanations are high variability of farm nutrient management even between farms of similar structure and errors when quantifying relevant parameters, e.g. during sampling, measurement or processing. Moreover, some variables (e.g. weather characteristics, differences in technologies and management) that play an essential role in describing N performance and its components may be missing from the set of determinants investigated in the models. For both aspects, further research is needed.

Overall, the outcomes of multiple regression analysis help identify ways to improve NUE on farm level and thus to reduce N waste. Due to the fact that several farm types were investigated on a great sample size and accurate farm accountancy data, targeted strategies can be derived for particular farm systems. To do so, the focus of our analysis was especially on complex farm structures so that we evaluated, among others, the role of both crop selection and diversity, as well as animal husbandry and manure utilisation and its interplay when optimising NUE and mitigating N waste on farm level.

4.2 Policy implications

This paper provides evidence that the N performance of farms is dependent on farm structural characteristics to some extent, and also on financial incentives. Farm structure can therefore be more effectively influenced by agri-environmental policies e.g. through incentive management, such as funding policies (positive incentive, e.g. subsidies) or restrictions (negative incentive, e.g. sanctions), rather than by focusing on regional and socio-economic characteristics. Most results obtained were coherent for both N performance indicators investigated, making it possible to derive firm conclusions.

Small farms and organic farming, whose role in mitigating climate change is much discussed, were found to make major contributions to improving N performance in German agriculture. Organic farming has been steadily increasing for years (number of farms and proportion of agricultural land) (DESTATIS 2022b). Due to political objectives at national level (SPD et al. 2021; BMEL 2022b) and EU level (European Commission 2022) to achieve at least 30% ecological UAA by 2030, this trend can be expected to continue and our results indicate that it is associated with N performance benefits. However, there are still unresolved aspects regarding demand for organic products in society, availability of organic fertilisers and yield potential as the world's population increases, total number of farms decreases and mean farm size increases over time. We found better N performance for regions with smaller farm structures (South) and very large farms (East), compared e.g. with the North region with medium-sized farms. Thus, policy should concentrate on raising farmer awareness and knowledge, technology and management, rather than on farm structural policies. Our results also showed that crop diversity *per se* is not crucial, but rather a well-chosen, low to medium diverse crop sequence. If crop selection and crop rotations have to be altered to cope with climate change (Schmitt et al. 2022), aspects of resource efficiency in particular should be considered in future management of crop rotations, in addition to climate-adapted varieties. Furthermore, payments for AECM within EU agricultural policy in particular were found to have a good effect on N performance, so our recommendation is to maintain and expand this policy measure. AECM seems to be of high relevance for improved N management, for which the monetary budget is determined at European Commission level but allocation and design are decided at national level (Latacz-Lohmann et al. 2019).

5 Conclusions

FarmB *per se* is known to be an appropriate N indicator, due to high relative and absolute degree of data reliability and certainty and high ease of use for users and control authorities, in particular with software-supported tools. In this study, we tested farm-NUE as a further N indicator, since it is becoming widely accepted as a meaningful and inclusive agri-environmental indicator in scientific research and political opinion. Also, German legislation already provides the framework for calculating farm-NUE, without any additional data collection efforts. For that, this indicator may play a key role for optimising N management as the added value is much higher than additional effort. This also applies to other NUE variations (at feed and field level), for which the corresponding data largely exist in official records and the added value in obtaining further information relevant for farm nutrient management is high.

FarmB methodology was adopted as a regulatory approach for official N reporting in Germany in 2017 but, following an evaluation process by scientific and administrative experts, an amended ordinance including a new and more ambitious assessment system, is to be developed in 2023 by federal authorities. Based on this change, we calculated FarmB as a preventive indicator and farm-NUE as an indicator of on-farm N performance, as the regulation provides the methodological framework for both. Our results provide a theoretical and quantitative basis for federal authorities to develop farm (type)-specific recommendations with regard to farm-NUE.

Also, we showed a novel methodological step for determining N performance indicators from farm accounting data in this study. This statistical calculation programme can be applied by multiple stakeholders such as policymakers, control authorities, consultants, or farmers, in order to serve different purposes, e.g. optimising N flows, monitoring, or controlling legally defined thresholds on farm level. As FADN is a database with a set of statistics being periodically produced and published for EU member states and beyond, the presented universal approach can be adopted on an international level with individual adaptations, if necessary.

Overall, the study provided new knowledge on the variation in the two N indicators investigated and its order of magnitude. This can be seen as the first step in NUE-benchmarking for farm types in Germany. However, for extensive farms with potential manure N imports and considerable BNF on grassland, particularly relevant for organic farming, our results are less reliable. Further research is needed to gain a deeper understanding of N flows on farm types with potential for improving efficiency and difficulties meeting current sustainability goals. These are mainly farms rearing animals, especially ruminants. The study also provided new knowledge on the significant effects of regional, farm structural, agronomic and socio-economic variables on N performance, which also enables the identification of structural patterns and strategies to reduce N waste. Since the variances of N indicators are high, it is of utmost importance to use large sample sizes with high quality data to show and interpret effects. The large number of studies that do not meet these criteria must be viewed with skepticism. In addition, our study revealed large potentials for improving NUE even without changing the existing farm structures. Thus, policy measures should address these efficiency reserves first, and if necessary even after improving NUE, adjust farm structures (e. g. reducing livestock density) as a second step. Also, it revealed the effectiveness of selected policy schemes and access to farm advice in moving toward balanced N management, justifying some current support policies.

List of abbreviations

ATD Atmospheric N deposition

AECM Agri-environment-climate measures

BMEL Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture)

BNF Biological nitrogen fixation

EU European Union

FarmB Farm-gate N balance

FADN Farm Accountancy Data Network

N Nitrogen

NUE Nitrogen use efficiency

OLS Ordinary Least Square

StdMean Standard error of the mean

StoffBilV Stoffstrombilanzverordnung (Ordinance on Substance Flow Analysis)

VIF Variance Inflation Factor

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Appendix

Table A1. Detailed information on the determinants investigated in multiple regression analysis.

Variables investigated	Type	Unit	Description
Large geographic regions	categorial	0: no; 1: yes	South, East, West, North
Natural yield potential	categorial	0: no; 1: yes	Low (<30 EMZ), Medium (30-50 EMZ), High (<50 EMZ)
Altitude	categorial	0: no; 1: yes	Low (<300 m), medium (300-600 m), high (>600 m)
Irrigated area	continual	ha/ha	
Farm size	continual	ha	
Organic manure - cattle	continual	kg N/ha	Organic manure (cattle origin) applied, gross
Organic manure -pig	continual	kg N/ha	Organic manure (pig origin) applied, gross
Organic manure - poultry	continual	kg N/ha	Organic manure (poultry origin) applied, gross
Organic manure - other animals	continual	kg N/ha	Organic manure (other animals origin) applied, gross
Organic manure - digestate	continual	kg N/ha	Organic manure (digestate origin) applied, gross
Wheat yield	continual	kg N/ha	Winter wheat
Rye yield	continual	kg N/ha	Winter rye
Winter grain yield	continual	kg N/ha	Winter barley, triticale, other winter cereals
Spring grain yield	continual	kg N/ha	Spring wheat, spring rye, durum wheat, oat, energy grain, other spring cereals
Maize yield	continual	kg N/ha	Grain maize, silage maize, CCM, energy maize
Rapeseed yield	continual	kg N/ha	Winter rape, spring rape
Sugar beet yield	continual	kg N/ha	
Potato yield	continual	kg N/ha	
Grassland yield	continual	kg N/ha	
Vegetable area (factor)	continual	ha/ha	
Grain legumes yield	continual	kg N/ha	Field bean, pea, soy, energy protein plants, other pulse
Other crops area (factor)	continual	ha/ha	
Crop diversity	categorial	0: no; 1: yes	Low (up to 3 different crops), medium (4 to 6 different crops), high (7 or more different crops)
Dairy production	continual	kg N/ha	
Production type	categorial	0: no; 1: yes	Organic, conventional
Farm size	categorial	0: no; 1: yes	Low (<50 ha), medium (50-180 ha), high (>180 ha)
Age	categorial	0: no; 1: yes	Low (<40 years), medium (40-60 years), high (>60 years)
School education	categorial	0: no; 1: yes	Low (no/in education, secondary school 9th class), medium (secondary school 10th class), high (university entrance diploma)
Agricultural education	categorial	0: no; 1: yes	Low (no/in education, medium (skilled worker), high (master craftsman´s diploma, university, school of engineering)
Operating profit	categorial	0: no; 1: yes	Low (<300 €/ha), medium (300-1000 €/ha m), high (>1000 €/ha)
Consulting services received	categorial	0: no; 1: yes	Low (<=2500 €), high (>2500 €)

Payments for AECM[1] received	continual	€/ha
Payments for compensation received	continual	€/ha
Machinery and external services	continual	€/ha
Number of employees	continual	heads

[1] *Payments received for agri-environment-climate measures, not including payments for ecological farming and payments for compensations.*

Table A2. Specification and results of the advanced multiple regression model for the Nitrogen balance (FarmB) and Nitrogen use efficiency (farm-NUE) on farm level (n = 5923).

Independent variables	**Description**	**Unit**	**Dependent variables**				**Scale type**					
			All		***Organic N application***				***Farm type***			
					< 50 kg N/ha		***> 50 kg N/ha***		***Arable, permanent***		***Animals, mixed***	
			N balance (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)	**N balance** (kg N/ha)	**NUE** (%)
			Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
Region												
Large geographic regions	South	0: no; 1: yes	-7.3*	3.7*	-5.1	3.0	-12.9*	1.2	-5.0	2.6	-9.9*	2.3*
	East	0: no; 1: yes	-9.2*	2.7*	-11.6*	10.9*	-8.7*	-1.3	-13.4*	11.0*	-8.1	-0.1
	West	0: no; 1: yes	0.4	0.4	-6.2*	5.9*	0.7	-1.3	-5.7	3.5	1.4	-0.5
	North	0: no; 1: yes										
Natural yield potential	low	0: no; 1: yes	3.7	-1.9	3.9	-2.2	1.0	-0.1	3.8	-3.0	0.9	-1.3
	medium	0: no; 1: yes	3.1	-0.5	3.0	-1.2	0.6	1.1	4.9	-4.4	-0.6	0.2
	high	0: no; 1: yes										
Altitude	low	0: no; 1: yes	15.5*	-4.5*	0.9	-6.4	9.1*	-4.1*	3.1	4.9	10.2*	-4.2*
	medium	0: no; 1: yes	18.7*	-9.3*	3.2	-7.3	15.6*	-7.2*	2.9	6.2	15.6*	-7.6*
	high	0: no; 1: yes										
Irrigated area (factor)		ha/ha	8.7	2.2	11.0	-0.8	-6.1	8.9	4.1	6.5	27.7	-4.5
Farm structural												
Organic manure - cattle		kg N/ha	0.9*	-0.4*	0.7*	-0.4*	0.9*	-0.2*	0.7*	-0.6*	0.8*	-0.3*
Organic manure - pig		kg N/ha	0.8*	-0.2*	1.2*	-0.9*	0.7*	-0.1*	1.1*	-0.2*	0.7*	-0.1*
Organic manure - poultry		kg N/ha	1.1*	-0.2*	1.4*	-0.7*	1.1*	-0.1*	0.8*	-0.1	1.1*	-0.1*
Organic manure - other animals		kg N/ha	0.5*	-0.4*	0.5	-0.9*	0.5*	-0.2*	1.2*	-1.2*	0.5*	-0.2*
Organic manure - digestate		kg N/ha	0.6*	-0.2*	0.6*	-0.4*	0.5*	0.0	0.8*	-0.7*	0.5*	-0.1*
Wheat yield		kg N/ha	0.0	0.2*	-0.1*	0.4*	0.1*	0.2*	-0.1*	0.2*	0.1	0.2*
Rye yield		kg N/ha	-0.1	0.3*	0.0	0.2	0.0	0.3*	-0.1	0.1	-0.1	0.3*
Winter grain yield		kg N/ha	0.0	0.2*	-0.3*	0.4*	0.3*	0.1*	-0.4*	0.4*	0.2*	0.1*
Spring grain yield		kg N/ha	0.0	0.2*	-0.3*	0.5*	0.2	0.0	-0.3*	0.4*	0.2	0.1
Maize yield		kg N/ha	-0.4*	0.4*	-0.8*	0.9*	-0.2*	0.3*	-1.0*	0.9*	-0.1*	0.3*
Rapeseed yield		kg N/ha	0.1	0.3*	0.0	0.1	0.2	0.3*	-0.1	0.0	0.3*	0.3*
Sugar beet yield		kg N/ha	-0.3*	0.5*	-0.4*	0.4*	-0.4*	0.4*	-0.5*	0.3*	-0.5*	0.4*
Potato yield		kg N/ha	0.0	0.3*	-0.3*	0.3*	0.4*	0.2*	-0.3*	0.2	0.3*	0.2*
Grassland yield		kg N/ha	-0.3*	0.2*	-0.3*	0.1	-0.2*	0.2*	-0.3*	0.2	-0.1*	0.2*
Vegetable area (factor)		ha/ha	12.0	8.3	-5.7	58.1*	21.2	31.9*	1.9	29.6*	-25.8	22.6
Grain legumes yield		kg N/ha	-0.1	0.2*	-0.1	0.7*	0.0	0.0	-0.3	0.7*	0.2	0.0
Other crops area (factor)		ha/ha	13.5*	-5.4*	-21.1*	21.5*	21.1	2.0	-19.4*	3.3	16.7	-2.2
Crop diversity	low	0: no; 1: yes	-13.1*	2.8*	-8.0*	-7.6*	-11.2*	1.1	-4.5	-5.5	-11.6*	1.5

	medium	0: no; 1: yes	-1.6	0.9	-3.7	0.4	-1.5	-0.7	0.0	-0.5	-1.7	0.4
	high	0: no; 1: yes										
Production type	organic	0: no; 1: yes	-24.3*	-0.4	-29.1*	5.1	-20.7*	0.8	-28.2*	-4.3	-20.7*	0.2
	conventional	0: no; 1: yes										
Socio-economic												
Farm size	low	0: no; 1: yes	-8.6*	4.9*	-9.0*	9.4*	-8.3*	4.4*	-13.4*	11.2*	-4.4	4.5*
	medium	0: no; 1: yes	-2.5	1.0	-5.1*	3.1	-3.1	0.6	-9.4*	6.3*	0.3	0.5
	high	0: no; 1: yes										
Age	low	0: no; 1: yes	3.0	-2.2	6.4*	-9.5*	-0.6	0.6	3.2	-5.6	1.7	0.1
	medium	0: no; 1: yes	1.3	-1.1	0.5	-1.4	1.8	-0.4	1.1	-0.4	1.3	-0.2
	high	0: no; 1: yes										
School education	low	0: no; 1: yes	-2.5	1.4	-3.7	2.4	-2.9	0.1	-2.3	0.4	-4.3	1.2
	medium	0: no; 1: yes	-5.6*	3.1*	-5.9*	3.5	-7.9*	0.8	-4.0	0.6	-8.4*	2.5*
	high	0: no; 1: yes										
Agricultural education	low	0: no; 1: yes	-2.2	1.0	-1.2	-0.1	-4.2	-0.9	1.3	-0.6	-4.0	-0.3
	medium	0: no; 1: yes	-3.5*	0.3	2.6	-3.4	-7.9*	0.5	2.8	-3.6	-7.1*	0.4
	high	0: no; 1: yes										
Operating profit	low	0: no; 1: yes	10.6*	-7.2*	3.3	0.6	14.5*	-7.5*	8.8*	-2.6	10.9*	-7.3*
	medium	0: no; 1: yes	4.9*	-5.0*	-1.8	4.9	8.3*	-4.8*	1.9	2.5	6.4*	-5.2*
	high	0: no; 1: yes										
Consulting services	low	0: no; 1: yes	9.7*	-1.5*	2.8	-0.8	14.0*	-1.3	-0.1	2.5	13.8*	-1.6*
	high	0: no; 1: yes										
Payments for AECM[1]		€/ha	-0.03*	0.01	-0.02	0.00	-0.03*	0.00	-0.02	-0.01	-0.03*	0.00
Compensation received		€/ha	-0.04	0.00	-0.04	0.03	-0.03	-0.01	-0.04	0.02	-0.04	-0.01
Machinery and external services		€/ha	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Number of employees		heads	0.12*	-0.05	0.12*	-0.13*	0.12	0.06	0.10	-0.11	0.24	0.04
Observations		n	5923	5923	2471	2471	3452	3452	1932	1932	3991	3991
Goodness of fit		R^2	0.43	0.20	0.19	0.09	0.33	0.22	0.18	0.06	0.37	0.17

Regression coefficients are shown in a way that positive values are to be understood as an increase of the indicator, negative values as a decrease.

[1] *Payments received for agri-environment-climate measures, not including payments for ecological farming and payments for compensations.*

**Significant regression coefficients (p-value < 0.05).*

Table A3. Specification and results of the advanced regression model estimated for the two N indicators investigated with different intensities of cattle manure application (n = 5923).

Independent variables	**Description**	**Unit**	**Dependent variables**	
			N balance (kg N/ha) Coefficient	**NUE** (%) Coefficient
Region				
Large geographic regions	South	0: no; 1: yes	**-7.5**	**3.5**
	East	0: no; 1: yes	**-9.1**	**2.7**
	West	0: no; 1: yes	0.4	0.5
	North	0: no; 1: yes		
Natural yield potential	low	0: no; 1: yes	**4.3**	-1.7
	medium	0: no; 1: yes	3.7	-0.4
	high	0: no; 1: yes		
Altitude	low	0: no; 1: yes	**14.7**	**-4.6**
	medium	0: no; 1: yes	**18.4**	**-9.0**
	high	0: no; 1: yes		
Irrigated area (factor)		ha/ha	7.6	1.8
Farm structural				
Organic manure - cattle	low	kg N/ha	**0.86**	**-0.39**
	medium	kg N/ha	**0.89**	**-0.40**
	high	kg N/ha	**0.98**	**-0.35**
Organic manure - pig		kg N/ha	**0.8**	**-0.2**
Organic manure - poultry		kg N/ha	**1.1**	**-0.2**
Organic manure - other animals		kg N/ha	**0.5**	**-0.4**
Organic manure - digestate		kg N/ha	**0.6**	**-0.2**
Wheat yield		kg N/ha	0.0	**0.2**
Rye yield		kg N/ha	-0.1	**0.3**
Winter grain yield		kg N/ha	-0.1	**0.1**
Spring grain yield		kg N/ha	0.0	**0.2**
Maize yield		kg N/ha	**-0.5**	**0.4**
Rapeseed yield		kg N/ha	0.0	**0.3**
Sugar beet yield		kg N/ha	**-0.4**	**0.4**
Potato yield		kg N/ha	-0.1	**0.2**
Grassland yield		kg N/ha	**-0.3**	**0.2**
Vegetable area (factor)		ha/ha	7.0	6.1
Grain legumes yield		kg N/ha	-0.1	0.1
Other crops area (factor)		ha/ha	**9.2**	**-7.0**
Crop diversity	low	0: no; 1: yes	**-13.7**	**2.2**
	medium	0: no; 1: yes	-2.2	0.5
	high	0: no; 1: yes		
Production type	organic	0: no; 1: yes	**-24.0**	0.1
	conventional	0: no; 1: yes		
Socio-economic				
Farm size	low	0: no; 1: yes	**-8.6**	**5.0**
	medium	0: no; 1: yes	-2.6	1.0
	high	0: no; 1: yes		
Age	low	0: no; 1: yes	3.1	-2.2
	medium	0: no; 1: yes	1.1	-1.1
	high	0: no; 1: yes		
School education	low	0: no; 1: yes	-2.3	1.5
	medium	0: no; 1: yes	**-5.6**	**3.1**
	high	0: no; 1: yes		
Agricultural education	low	0: no; 1: yes	-2.1	1.0
	medium	0: no; 1: yes	**-3.4**	0.3
	high	0: no; 1: yes		
Operating profit	low	0: no; 1: yes	**11.1**	**-6.9**
	medium	0: no; 1: yes	**5.5**	**-4.6**
	high	0: no; 1: yes		
Consulting services	low	0: no; 1: yes	**9.5**	**-1.5**
	high	0: no; 1: yes		

Payments for AECM[1]	€/ha	**0.0**	0.0
Compensation received	€/ha	0.0	0.0
Machinery and external services	€/ha	0.0	0.0
Number of employees	heads	**0.1**	-0.1
Observations	n	5923	5923
Goodness of fit	R^2	0.43	0.20

Regression coefficients are shown in a way that positive values are to be understood as an increase of the indicator, negative values as a decrease. Bold numbers: significant at the p < 0.05 level.

[1] *Payments received for agri-environment-climate measures, not including payments for ecological farming and payments for compensations.*

Table A4. Specification and results of the advanced regression model estimated for the two N indicators investigated with different intensities of pig manure application (n = 5923).

Independent variables	**Description**	**Unit**	**Dependent variables**	
			N balance (kg N/ha) Coefficient	**NUE** (%) Coefficient
Region				
Large geographic regions	South	0: no; 1: yes	**-7.2**	**3.6**
	East	0: no; 1: yes	**-8.8**	**2.4**
	West	0: no; 1: yes	0.2	0.3
	North	0: no; 1: yes		
Natural yield potential	low	0: no; 1: yes	3.8	-1.9
	medium	0: no; 1: yes	3.3	-0.6
	high	0: no; 1: yes		
Altitude	low	0: no; 1: yes	**15.6**	**-4.9**
	medium	0: no; 1: yes	**18.7**	**-9.7**
	high	0: no; 1: yes		
Irrigated area (factor)		ha/ha	9.1	0.5
Farm structural				
Organic manure - cattle		kg N/ha	**0.9**	**-0.4**
Organic manure - pig	low	kg N/ha	**1.09**	**-0.39**
	medium	kg N/ha	**0.87**	**-0.28**
	high	kg N/ha	**0.76**	**-0.20**
Organic manure - poultry		kg N/ha	**1.1**	**-0.2**
Organic manure - other animals		kg N/ha	**0.5**	**-0.4**
Organic manure - digestate		kg N/ha	**0.6**	**-0.2**
Wheat yield		kg N/ha	0.0	**0.2**
Rye yield		kg N/ha	-0.1	**0.3**
Winter grain yield		kg N/ha	-0.1	**0.2**
Spring grain yield		kg N/ha	0.0	**0.2**
Maize yield		kg N/ha	**-0.4**	**0.4**
Rapeseed yield		kg N/ha	0.1	**0.3**
Sugar beet yield		kg N/ha	**-0.4**	**0.4**
Potato yield		kg N/ha	0.0	**0.3**
Grassland yield		kg N/ha	**-0.3**	**0.2**
Vegetable area (factor)		ha/ha	12.0	7.8
Grain legumes yield		kg N/ha	-0.1	**0.2**
Other crops area (factor)		ha/ha	**13.8**	-4.3
Crop diversity	low	0: no; 1: yes	**-13.1**	**2.8**
	medium	0: no; 1: yes	-1.4	0.8
	high	0: no; 1: yes		
Production type	organic	0: no; 1: yes	**-24.3**	0.2
	conventional	0: no; 1: yes		
Socio-economic				
Farm size	low	0: no; 1: yes	**-9.0**	**5.1**
	medium	0: no; 1: yes	-2.8	1.2
	high	0: no; 1: yes		
Age	low	0: no; 1: yes	2.9	-2.2
	medium	0: no; 1: yes	1.4	-1.1
	high	0: no; 1: yes		
School education	low	0: no; 1: yes	-2.1	1.2
	medium	0: no; 1: yes	**-5.4**	**3.0**
	high	0: no; 1: yes		
Agricultural education	low	0: no; 1: yes	-2.0	0.8
	medium	0: no; 1: yes	**-3.6**	0.3
	high	0: no; 1: yes		
Operating profit	low	0: no; 1: yes	**10.5**	**-6.8**
	medium	0: no; 1: yes	**4.6**	**-4.6**
	high	0: no; 1: yes		
Consulting services	low	0: no; 1: yes	**9.7**	**-1.6**
	high	0: no; 1: yes		
Payments for AECM[1]		€/ha	**0.0**	0.0

Compensation received	€/ha	0.0	0.0
Machinery and external services	€/ha	0.0	0.0
Number of employees	heads	**0.1**	0.0
Observations	n	5923	5923
Goodness of fit	R^2	0.428	0.204

Regression coefficients are shown in a way that positive values are to be understood as an increase of the indicator, negative values as a decrease. Bold numbers: significant at the $p < 0.05$ level.

[1] *Payments received for agri-environment-climate measures, not including payments for ecological farming and payments for compensations.*

Table A5. Nitrogen use efficiency (NUE) at farm level under consideration of additional N inputs from atmospheric N deposition based on livestock density and biological N fixation based on mineral fertiliser intensity (n = 5919).

Scale type	Sample size (n)	Indicator	Modifications		
			None	**N input - Atmospheric N deposition[1]**	**N-Input - Biological N fixation[2]**
All	5919	NUE (%) median	64	64	64
Arable	1518	NUE (%) median	100	100	100
Dairy	1744	NUE (%) median	45	45	45
Other cattle	570	NUE (%) median	62	62	**60**
Pig, poultry	541	NUE (%) median	55	**52**	55
Permanent	410	NUE (%) median	95	95	95
Mixed	1136	NUE (%) median	64	64	64

[1] *For intensive pig and poultry farms (>1.8 LSU/ha), atmospheric N deposition around 30 kg N/ha is assumed, for other pig and poultry farms 10 kg N/ha, based on https://gis.uba.de/website/depo1/de/index.html.*

[2] *For other cattle and grazing livestock farms, biological N fixation (BNF) on grassland is assumed according to mineral fertiliser intensity, so that 0 kg mineral N/ha = 65 kg N/ha BNF, 1-30 kg mineral N/ha = 30 kg N/ha BNF, >30 kg N mineral N/ha = 10 kg N/ha BNF; based on assumptions made in Osterburg (2007) ISBN 978-3-86576-031-9, p. 259.*

Table A6. Nitrogen use efficiency (NUE) at farm level under consideration of externalised nitrogen (N) from purchased feed and sold manure with low, medium and high assumptions on external N efficiency, and combination of low and high N efficiency (n = 5919).

Scale type	**Sample size (n)**	**Indicator**	**Externalities**								
			None	**Feed import N efficiency**			**Manure export N efficiency**			**Combined**	
				High[1]	Medium[2]	Low[3]	High[4]	Medium[5]	Low[6]	High[7]	Low[8]
All	5919	NUE (%) median	64	52	48	44	62	62	61	51	43
Arable	1518	NUE (%) median	100	99	98	98	100	100	100	99	98
Dairy	1744	NUE (%) median	45	33	29	25	42	41	41	31	23
Other cattle	570	NUE (%) median	62	52	50	45	61	61	61	52	44
Pig, poultry	541	NUE (%) median	55	38	34	28	50	49	48	35	25
Permanent	410	NUE (%) median	95	95	95	95	95	95	95	95	95
Mixed	1136	NUE (%) median	64	54	51	47	63	63	63	54	47

[1] *NUE of 60% is assumed for purchased feed.*

[2] *NUE of 50% is assumed for purchased feed.*

[3] *NUE of 40% is assumed for purchased feed.*

[4] *NUE of 30% is assumed for sold manure.*

[5] *NUE of 20% is assumed for sold manure.*

[6] *NUE of 10% is assumed for sold manure.*

[7] *NUE of 60% is assumed for purchased feed, NUE of 30% is assumed for sold manure.*

[8] *NUE of 40% is assumed for purchased feed, NUE of 10% is assumed for sold manure.*

5 Nitrogen use efficiency on dairy farms with different grazing intensities in northwestern Germany (Paper III)

This research article (Paper III) has been published as:

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In this thesis, the last version of the accepted draft is added in the next pages.

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Erratum: Nitrogen use efficiency on dairy farms with different grazing systems in northwestern Germany (2020 *Environ. Res. Commun.* **2** 105002)

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Due to an error in production, there are two equations in this paper that have been printed incorrectly and should be corrected as listed below.

In equation (4), the closing bracket is missing and should appear as below:

$$\begin{aligned} Manure\ N\ [storage] &= (Manure\ N \times Ratio\ pasture \times N\ losses\,[outdoor]) \\ &\quad + (Manure\ N \times Ratio\ indoor \times N\ losses\ [indoor_{\mathrm{1}}]) \end{aligned}$$

In equation (9), the last term 'Manure N soldexport' should read 'Manure N export' as below:

$$\begin{aligned} Total\ N\ balance = {} & Purchased\ feed\ N\ intake \\ & + N\ fertilizer\ and\ manure\ import \\ & - Milk\ N - Meat\ N - Harvest\ N\ sold \\ & - Manure\ N\ export \end{aligned}$$

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PAPER

Nitrogen use efficiency on dairy farms with different grazing systems in northwestern Germany

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Keywords: nitrogen use efficiency, N balance, N surplus, substance flow analysis, nutrient management, sustainable agriculture

Supplementary material for this article is available online

Abstract

Agricultural production is often accompanied by nitrogen (N) losses causing negative environmental effects. In order to assess dairy farms´ N management, appropriate indicators based on robust farm data need to be addressed. This study investigated N balance and N use efficiency (NUE) as a function of grazing intensity on specialized dairy farms in northwestern Germany. For that, 30 farms were grouped according to pasture management from full grazing to zero grazing: >10 h in group 1, 6 to 10 h in group 2, <6 h in group 3, and group 4 without pasture access. Based on multiple farm data, substance flow analysis was carried out. Subsequently, the data were analyzed according to the relevant indicators N surplus and NUE on feed-, field- and farm-level. The results revealed N surpluses on all farms, with the average N surplus tending to decrease from 259 to 179 kg N ha^{-1}, and farm-NUE to increase from 40 to 50 %, from full grazing to zero grazing management systems. There were considerable differences between the N balances calculated in this study and those reported by farms as part of statutory net N soil surface balance reporting under the German regulatory law. In conclusion, the N indicators were suitable to compare farm performance among and within different dairy farming systems. When comparing indicator values there is a need to consider the methodology applied, the system boundaries set, and the origin and quality of data used.

List of abbreviations

ATD	Atmospheric deposition
BNF	Biological nitrogen fixation
CP	Crude protein
DC	Dairy cattle
DüV	Düngeverordnung (Fertilizer Application Ordinance)
ECJ	European Court of Justice
ECM	Energy-corrected milk
IRR	Internal Roughage Recording
LSU	Livestock unit
N	Nitrogen
NutC	Nutrient Comparison
NH_3	Ammonia
NO_3^-	Nitrate
NUE	Nitrogen use efficiency
SFA	Substance flow analysis
StoffBilV	Stoffstrombilanzverordnung (Ordinance on Substance Flow Analysis)
UAA	Utilized agricultural area

1. Introduction

1.1. Problem

Nitrogen (N) is an essential nutrient in agricultural production and its use has intensified in recent decades, to meet growing global food needs. However, overuse of N fertilizers in some regions has led to various environmental problems (FAO 2018). Since N appears in environmental media (i.e., air, water, and soil) in different reactive forms, it has multiple impacts. Gaseous N compounds can have negative effects on air quality and climate warming, while nitrate mobilized through leaching and run-off impairs water quality. The latter leads to high nutrient accumulation in soils and waters (eutrophication), e.g. due to inadequate application of manure, which poses a serious environmental hazard (Fields 2004, Leip *et al* 2015). Eutrophication due to increased emissions of nitrate and phosphate results mainly from nutrient surpluses in agriculture (Leip *et al* 2015, SRU 2015, Jansson *et al* 2019).

The anthropogenic influence on the N cycle is primarily related to production and use of N fertilizers for agriculture, with atmospheric molecular unreactive N in the order of 120 million tons being converted annually into reactive forms such as ammonium, nitrate, and nitrous oxide in the early 2000s (Rockström *et al* 2009a). Nitrogen is defined as one of three 'planetary boundaries', along with climate change and biodiversity loss, for which the tolerable limits are being exceeded (Rockström *et al* 2009b). Therefore, there is a need to apply organic and mineral N fertilizers in a more efficient and sustainable way, in order to produce sufficient food while reducing negative environmental impacts (The Federal Government 2016).

Agriculture in western and northwestern Germany is characterized by high livestock numbers per hectare (ha), with high N surpluses that often result in the legal nitrate threshold values in groundwater being exceeded (LWK Nordrhein-Westfalen 2018, Meergans and Lenschow 2018, LWK Niedersachsen 2019). Lower Saxony is one such region, with intensive dairy production resulting in high application rates of manure, e.g., 175 kg N ha^{-1} annually in the administrative district of *Weser-Ems* (Neuenfeldt and Gocht 2017, LWK Niedersachsen 2019 based on Gocht and Röder 2014). Due to subsidies for renewable energy (BMWi 2017), biogas facilities have also expanded in the region, using energy crops such as maize and manure as the main substrates. Nutrient-rich digestate is returned to neighboring fields, since digestate and/or manure transport is usually not cost-effective (Schindler 2009). Dairy farming in Lower Saxony was traditionally based on pasture grazing during summer (Schaak and Musshoff 2018), but the pasture area has been declining (DESTATIS 2019). Large farms now commonly apply zero grazing, while the number of dairy farms with integrated pasture management is decreasing (Neuenfeldt *et al* 2019).

1.2. Legal background

Legal requirements at national and international level have been introduced to reduce N losses from agriculture, sustain long-term food security, and ensure the same standard of living for future generations (*intergenerational equity*). These are in compliance with national and international environmental objectives, i.e., improving water quality, reducing ammonia emissions, and combating climate change (De Vries *et al* 2013, SRU 2015).

To this end, the European Union (EU) Nitrates Directive aims to reduce and prevent further pollution of waters caused by nitrates from agriculture, in particular through fertilization, by promoting the use of 'good farming practices' (European Council 1991). Under the directive, EU Member States are obliged to draw up national four-year action programs to reduce nitrate pollution (European Commission 2019).

The upper limit for groundwater (50 mg $NO_3^- L^{-1}$) defined in the Nitrates Directive has been exceeded at many monitoring sites in recent decades. Therefore, an infringement procedure against Germany was launched in 2013 (Salomon *et al* 2015) and resulted in a conviction in June 2018 (ECJ 2018). Following an inadequate amendment in 2017 (Kuhn *et al* 2020), efforts to comply with the Nitrates Directive led to tightening of the German Fertilizer Application Ordinance (Düngeverordnung, DüV) in 2020. It also led to abolition of Nutrient Comparison (NutC), a soil surface N and P balance reporting which had been obligatory since 1996 in Germany. Due to shortcomings of this balance approach, a farm-gate balance was introduced in 2018 through the Ordinance on Substance Flow Analysis (Stoffstrombilanzverordnung, StoffBilV). However, StoffBilV has not been part of Germany's action program to comply with the EU Nitrates Directive, but it was initiated in order to achieve the target for sustainable nitrogen management of the German Sustainable Development Strategy (The Federal Government 2016, StoffBilV 2017).

1.3. Indicators for evaluation of N balances

Agri-environmental indicators are characteristic numbers for estimating the environmental impact of agricultural production systems (EEA 2005, OECD 2013, Eurostat 2017). These are used: (1) for national and international reporting, (2) as determining factors for agri-environmental policy measures, (3) in the context of voluntary single-farm environmental information systems, and (4) to inform the broader public by illustrating agri-environmental relationships (Eurostat 2017). Different countries use differing methodologies for calculating these indicators (Klages *et al* 2020). This should be considered when setting indicative target values, which can lead to challenges in terms of national and cross-country comparability of reference or benchmark values (Eurostat 2018).

The nutrient balance of a farm is a relevant indicator for analysis of nutrient management. Agricultural nutrient balances can be distinguished according to the system boundary (e.g., farm-gate, soil surface), the nutrients they include (e.g., phosphorus or N), and whether N emissions from volatilization in animal stables, manure storage, and manure application to soil are excluded (*net balance*) or included (*gross balance*) (Eurostat 2013). The surplus/deficit identified through comparison of all inputs and outputs for a farm or agricultural sector represents the potential threat to the environment and the supply of nutrients to the soil (Eurostat 2019a).

Nitrogen use efficiency (NUE) is another key parameter used for evaluation of farm nutrient balance, as an indicator of resource use efficiency. It is calculated as total N removals over total N inputs and provides an indication of e.g., kilograms (kg) N incorporated into crop products per kg N input (PARCOM 1993, UNECE 2014). Production system, technologies, type and level of management have a strong influence on both N balance and NUE (Leip *et al* 2011, Eurostat 2018). As N surpluses are particularly high in intensive livestock farming areas, these regions are often the main target of efforts to increase NUE (Arriaga *et al* 2009, Gourley *et al* 2011b, Kanter *et al* 2020).

According to Powell *et al* (2010), NUE can be determined on three levels; (a) feed conversion (feed-NUE), (b) manure and fertilizer conversion into crops and pasture (field-NUE), and (c) farm-NUE, defined as the ratio between N exports (sold milk, crops, animals, losses leaving the farm) and N imports (feed, fertilizer, atmospheric deposition (ATD), biological N fixation (BNF)).

Substance flow analysis (SFA) is used for quantifying mass flows and for assessing nutrient fluxes through agricultural systems. SFA is based on input-output flows of every process along the supply chain, and processes connected to each other within the system. Thus the approach is useful for identifying ‘hotspots’ of nutrient losses within the on-farm N cycle, as it provides information about the type and extent of losses (environmental pressure), but not about impacts on the environment (Gerber *et al* 2014). In order to generate an SFA, large amounts of accurate data are required, which are often not available or accessible on farm scale. Assumptions can be useful, but they make the result less precise and relevant. Thus, due to the time and data requirements, SFA can be difficult to apply.

1.4. Research gap

There is copious national and international literature focusing on nutrient balances and NUE of dairy farms. Nutrient balancing in agriculture at different reference levels (e.g., soil, farm) has been in the scientific spotlight for decades (e.g., Harenz *et al* 1992, Bach *et al* 1997). Research regarding N balance and NUE at *farm* level and its meaning for agricultural and political actors is described by Powell *et al* (2010), Velthof *et al* (2009), Oenema *et al* (2003), and others. Feeding studies have found that ratio of roughage and concentrates has effects on NUE (Velthof *et al* 2009, Akert *et al* 2020), specifically through affecting milk production (Shortall *et al* 2017), and the amount of manure (Castillo *et al* 2000, Baron *et al* 2002, Arriaga *et al* 2009). Gourley *et al* (2011a) investigated contrasting dairy production systems and the impact on feed-NUE in different regions in Australia and found generally lower NUE on grazing-based dairy farms. For farm-NUE, temporal differentiation in pasture management has not been considered in previous studies (Scheringer 2002, Gourley *et al* 2011b). Thus there is a knowledge gap regarding farm-NUE of dairy farms with similar operating structures, but different pasture management systems, in intensive grassland regions.

1.5. Objectives and overall research approach

The overall aim of the present study was to compare N surpluses and NUE on dairy farms with different grazing systems in northwestern Germany and assess whether the data source affected the results. For livestock farms in particular, analysis of possible N flows at single farm level is of major relevance for identifying the potential for improving efficiency. Thus, key variables were investigated to identify interdependencies between NUE and grazing intensity. Dairy farms in Lower Saxony were selected for the study on the basis of similar farm structure and being located in the same region, to ensure similar environmental factors, e.g., soil type and climate. Pasture management systems on the farms ranged from highly intensive (full) grazing to zero grazing, and their potential for sustainable management of limited resources was compared. In this context, an attempt was made to link the comparison of farm-NUE with SFA based on (1) comprehensive farm data and (2) multiple sets of information obtained from different data sources, in order to cope with data implausibilities and to identify potential N inefficiencies. The overall intention was to make recommendations for actions by political actors designing environmental protection measures. Therefore, the following hypotheses were formulated:

H1. NUE and total N balance differs according to the grazing system.

H2. Different data qualities need plausibility checks in order to obtain robust and reliable results on analyses of NUE and total N balance.

2. Material and methods

2.1. Data

The farm data used in the study were obtained from a joint research project funded by the Federal State of Lower Saxony with the collaboration of eight national scientific, advisory and administrative institutions, which analyzed dairy production systems in that region between 2013 and 2018. The project focused on comparison of zero grazing and several pasture management systems on a total of 63 conventional full-time dairy farms. Farm selection was conducted with the help of the Chamber of Agriculture of Lower Saxony, whereas cubicle housing, a minimum herd size of 60 *Holstein-Friesian* or *Red-Holstein* dairy cows, and participation at routine herd data recording were the selection criteria. From around 10,700 dairy farms in Lower Saxony where approximately 60% having a minimum herd size of 60 cows in year 2015 (DESTATIS 2020), a total of 80 farms met the selection criteria of the project and were asked by the Chamber of Agriculture to participate, resulting in 63 farms to be willing. All these were located in the intensive grassland regions of Lower Saxony (Isselstein *et al* 2018, Armbrecht *et al* 2019).Long-term mean annual air temperature and precipitation throughout the region are 8.6 °C and 745 mm, respectively (DWD 2018). The dominant soil types are sandy soils and heavy loams in inland parts and clay soils in coastal areas (Roßberg *et al* 2007). Application rate of organic and organo-mineral N fertilizer is slightly below the threshold value of 170 kg N ha^{-1} a^{-1} stipulated in DüV, e.g., in Leer county, in which four farms are located, the mean application rate was 164 kg N ha^{-1} a^{-1} in 2018 (LWK Niedersachsen 2019).

Detailed descriptions of the farms, the regional structure of dairy farming, and methods of data acquisition for the project can be found in Armbrecht *et al* (2019), Hartwiger *et al* (2018), and Isselstein *et al* (2018). As a basis for calculations in the project, the following data were acquired from the farms, supported by on-site visits 2013–2016, which were documented in varying degrees of completeness:

- Monthly milk performance and quality data, providing data on milk production and its nutritional value
- Annual nutrient balances (according to Article 8 of DüV), providing data on manure and mineral fertilizer application volume, harvested quantities, and other parameters for the calendar year (January-December), crop/fiscal year (July-June), or forage year (May-April)
- Animal traceability and information system, providing animal data
- Multi-year seasonal on-farm feed rations recordings collected by the Chamber of Agriculture of Lower Saxony, providing data on feed composition and nutritional value
- Delivery notes for purchased feeds
- Internal Roughage Recording (IRR), providing farm-individual data on actual roughage quantities harvested, stored and utilized, and verified by the Chamber of Agriculture
- Data from the Integrated Administration and Control System on arable land, cultivated crops, grassland and livestock numbers.

In the present study, project farms for which data for the selected reference year (2014) were incomplete were excluded, resulting in a total of 30 dairy farms. In terms of dairy farm type, the sample included 12 grassland farms and 18 forage production farms, based on a classification relating to proportion of grassland (LfL 2018a). The farms were divided into the following four groups, based on grazing intensity on pasture:

- Group 1 ($n = 7$): full grazing system, with more than 10 h daily grazing
- Group 2 ($n = 8$): half-day grazing system, with 6–10 h daily grazing
- Group 3 ($n = 10$): part-time grazing system, with up to 6 h daily grazing
- Group 4 ($n = 5$): year-round indoor system, zero grazing.

Pasture access is provided for at least 120 days per year on farms in groups 1–3. Nitrogen balance was calculated using farm data on number of cattle, milk yield, roughage production, grazing time, purchased feed concentrates, and use of N fertilizers. Input and output flows were then calculated for each farm as required by StoffBilV (2017) and DüV (2017), following the approach proposed by Schüler *et al* (2016).

Table 1 gives an overview of all farms in the different groups. Farm structure information, such as proportion of grassland in total agricultural land and characteristics related to livestock farming, is also shown.[1]

2.2. Substance flow analysis

2.2.1. System boundary

The observed N flows at farm level were linked to the methodology of farm-gate balancing (e.g., Nevens *et al* 2005, Machmüller and Sundrum 2016) defined in StoffBilV (2017), with additional consideration of internal N flows (e.g., roughage, manure). The farm-gate balance refers to the farm boundaries and records N in all products that enter and leave the farm. Gross farm-gate balance according to StoffBilV (2017) was calculated by grouping the N flows as follows:

Inputs: Fertilizers (manure of animal origin, other organic fertilizers, mineral fertilizers), soil additives, growth media, feedstuffs, seeds including plant material, purchase of animals, BNF, ATD, other substances.

Outputs: Plant products, animal products, fertilizers (manure of animal origin, other organic fertilizers, mineral fertilizers), soil additives, growth media, feedstuff, seeds including plant material, dead animals, other substances.

As a gross balance calculation was conducted, factors for losses from manure volatilization in animal stables, in storage, and during application to soil were considered according to DüV (2017), in order to analyze the entire nutrient flows and to allow for comparison with NutC parameters.

Losses: Standard factors for losses due to N emissions from semi-liquid indoor manure according to DüV (2017) from (a) volatilization in stables and storage (15%) and (b) manure application to soil (15%) and (c) total N emissions from animal excretions on pasture (75%).

2.2.2. Calculation of N flows

The N surplus and NUE of the different groups of farms, and the variation within the groups, were analyzed. By comparing the inputs (manure, mineral N fertilizers, etc), outputs (milk, meat, etc) and other relevant parameters (plant uptake, storage losses, yield losses) of the 30 dairy farms in the sample, surpluses were quantified and inefficiencies in substance flows were identified. SFA was carried out to assess NUE, assuming N flows in 'Boxes 1–7' below, following the approach in Schüler *et al* (2016), with certain modifications. These included (a) manure N losses, in compliance with the regulatory framework in Germany, (b) 'stocks', in order to more accurately reflect actual roughage management; and (c) factor-based pasture uptake, avoiding the approach of derivation based on energy balance due to need-based inputs of roughage, and concentrates. Alternatively, the pasture uptake derived from energy requirements and actual feed rations can lead to inhomogeneous up to negative uptake rates and thus to incorrect assumptions, as over-consumption of feed and forage is not depicted in a strictly need-based estimation.

In the following, we describe the subsystems ('boxes') of the SFA as illustrated in figure 1.

2.2.2.1. Box 1 Crop production

Box 1 quantified N inputs entering the field and N outputs leaving the field. The N inputs to this box were farm-produced and imported manure, mineral fertilizer, ATD, and BNF. The N outputs were plant products for export (cash crops), and roughage (maize and grass remaining in the farm system).

The N quantities removed by cash crops and roughage were subtracted from the sum of N quantities applied in fertilizers. The annual quantities in excreta used as manure (feces, urine, litter) and the corresponding N concentrations were taken from the internal obligatory nutrient balance reports in NutC (Under Article 8 of DüV 2017) as well as the quantities of purchased mineral fertilizers and BNF. For ATD, an additional region-specific input of 20 kg N ha^{-1} was included in the calculation, as required by StoffBilV (2017) and UBA (2019). The N quantities and qualities harvested in cash crops and roughage were also taken from NutC. Manure N quantities from pasturing were deduced from the proportion of gross manure entering the 'pasture system' and utilized as 'pasture fed', as a function of the grazing intensity in hours and herd size. Manure N losses of 75% on pasture according to DüV (2017) were taken into consideration. Thus, balance 1 provided information on the amount of N not used by crops, and remaining in the soil or lost in the neighboring environment (equation (1)):

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[1] A livestock unit (LSU) equal to 500 kg living biomass. A conversion factor from DüV (2017) was used to determine the number of LSU: a dairy cattle or heifer is 1 LSU, a young cattle (1-2 years old) is 0.7 LSU, and a calf (up to 1 year old) is 0.3 LSU. Since other age limits were used in the present study, a mean value of 0.5 LSU was used for a calf (up to 1.5 years old) 0.85 LSU for a heifer (from 1.5 years old up to the first calving). Calves and heifers were grouped as 'young cattle' in the study.

Table 1. Farm-specific data on farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing) for the reference year 2014.

		Utilized agricultural area [ha]	Grassland [% of UAA][a]	Grazing time [hours/DC/a]	Dairy cattle	Young cattle	Milk yield [kg ECM/DC/a]	Milk protein [%][b]	Livestock units	Area-related LSU [LSU/ha UAA]
Group 1	Mean	108	69	3 177	125	106	8741	3.39	189	1.7
(n = 7)	Min–max	68–178	24–97	2430–4000	64–225	45–171	6334–9964	3.32–3.50	106–337	1.4–2.2
	SD	42	31	587	56	44	1146	0.08	84	0.3
	Median	86	86	3 233	116	105	9028	3.34	178	1.7
Group 2	Mean	117	81	1 706	121	131	8657	3.40	199	1.8
(n = 8)	Min–max	65–243	62–100	1556–1978	83–229	80–233	7549–10228	3.36–3.52	131–356	1.3–2.2
	SD	57	17	172	46	58	846	0.05	72	0.3
	Median	102	78	1 617	105	105	8443	3.38	169	1.8
Group 3	Mean	118	71	1 276	129	136	8874	3.34	209	1.9
(n = 10)	Min–max	57–245	41–95	1048–1464	88–215	57–330	7312–10383	3.19–3.48	122–408	1.1–2.2
	SD	55	15	146	37	74	1014	0.08	79	0.3
	Median	103	71	1241	122	126	8587	3.33	197	1.9
Group 4	Mean	118	51	24	182	119	9180	3.42	251	2.2
(n = 5)	Min–max	89–143	26–72	0–120	100–263	0–205	6789–10209	3.38–3.47	167–382	1.2–3.0
	SD	20	17	54	69	76	1372	0.04	79	0.7
	Median	120	53	0	158	118	9695	3.41	238	2.0

UAA = utilized agricultural area; DC = dairy cattle; ECM = energy-corrected milk; LSU = livestock unit.

[a] According to interviews with farmers, alternatively from *Agricultural Aid Lower Saxony Digital.*

[b] Three farms with average values of the study sample.

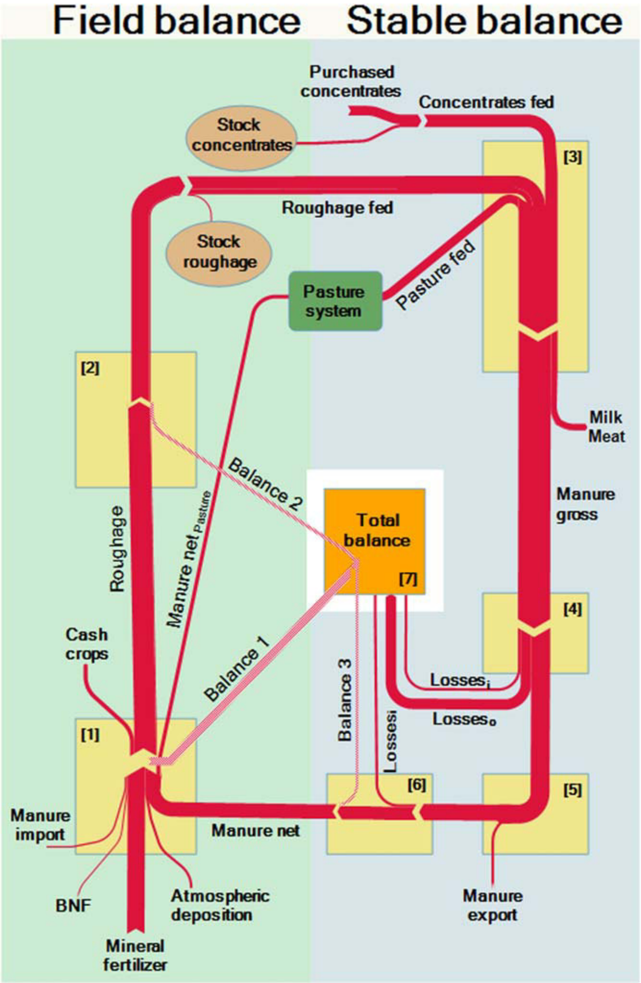

Figure 1. Example of nitrogen flow analysis for a dairy farm. Boxes 1–7 indicate points of even mass balances for nitrogen (own design following the sample representation in Schüler *et al* 2016).

$$
\begin{aligned}
\mathit{Balance}\ 1 = {} & \mathit{Mineral\ fertilizer\ N} + \mathit{Manure\ N}_{\mathit{NutC}}[\mathit{total\ net}] \\
& + \mathit{Legumes\ N} + \mathit{Atmosphere\ N} - \mathit{Harvest\ N\ sold} \\
& - \mathit{Roughage\ N} - \mathit{Manure\ N}_{\mathit{NutC}}[\mathit{outdoor\ net}]
\end{aligned} \qquad (1)
$$

2.2.2.2. Box 2 Roughage storage

For Box 2, two different approaches were used to document the N quantities removed by roughage. As N inputs, internal NutC records on N removals were used, including average roughage yields from previous years. As N outputs, the IRR assessment of actual annual N removals from roughage was used. Thus, balance 2 provided information on the difference between reported and estimated amount of N removed by roughage (equation (2)):

$$
\mathit{Balance}\ 2 = \mathit{Roughage\ N}\ [\mathit{NutC}] - \mathit{Roughage\ N}\ [\mathit{IRR}] \qquad (2)
$$

2.2.2.3. Box 3 Feed storage and animal stable

Box 3 quantified N inputs entering and N outputs leaving the livestock production systems. The N inputs in this box were from concentrates, roughage, and pasture feed. The N outputs were manure, milk, and meat.

First, the daily intake of roughage per dairy cattle was calculated based on multi-year seasonal feed rations recordings, providing data on quantities and crude protein (CP) values. For CP, an N content of 6.25% was assumed (Gourley *et al* 2011a, Koesling *et al* 2017, Leip *et al* 2019). For young cattle (0–24 months), a factor for roughage intake of 0.3 compared with the daily intake of dairy cattle was used, which is in line with recommended values in GfE (2001), DüV (2017), and LfL (2018b). The feed ration per animal was then multiplied by the number of livestock and extrapolated to one year, resulting in total N uptake from roughage. This value was subtracted from the N quantities removed by roughage measured in IRR, giving the change in roughage feedstock.

Second, concentrated feed ration per dairy cattle and day was calculated based on the feed rations recordings. A factor for concentrated feed intake of 0.1 was assumed for young cattle, considering the average feed ration based on farm data. Total N uptake from concentrates was deduced from the year's rations recordings multiplied by the number of livestock. The resulting sum was subtracted from total N in annually purchased concentrates, giving the change in concentrate feedstock. This consideration of stocks is a further development of the methodology proposed by Schüler *et al* (2016), as the available feed quantities do not correspond to the actual rations fed.

Third, the N quantities removed by grazing were calculated, based on the on-farm annual grazing intensity in hours and assumed pasture uptake of 0.4 kg hr^{-1} (A. Lasar, personal communication, April 23, 2019), on the basis of assessments of animal nutrition by experts involved in the project. The dry matter quantity of pasture uptake per dairy cattle and year was interpolated by relating it to on-farm annual grazing hours. Finally, this amount was divided by the CP content of pasture (18.8%), and the figure obtained was divided by the N content of CP, resulting in total N uptake through pasture grazing (Hartwiger *et al* 2018). In a further step, this value was subtracted from the amount of manure on grazing land as shown in Box 1, indicating over- or undersupply of N on pasture.

Fourth, the total amounts of N needed for milk and meat production were added up and compared to total N uptake, with the deficit resulting in the amount of N from manure (equation (3)), following Osterburg and Schmidt (2008). For calculating annual milk production, on-farm daily milk production rate per dairy cattle was extrapolated to one year and dairy cattle herd. Again, this amount was divided by the measured on-farm CP content (min-max 3.19%-3.52%) and then divided by the N content of milk CP (6.38%) resulting in the total N output through milk production. For the increase in living biomass (meat production), a rate of weight increase of around 0.7 kg d^{-1} in young cattle was assumed (LfL 2018b). The N output due to meat production in young cattle was calculated by setting the CP content of meat at 20%. Therefore, all parameters needed in order to derive the total amount of manure N were known:

$$\begin{aligned} Manure\ N\ [gross] = {} & Roughage\ N\ uptake + Concentrates\ N\ uptake + Grazing\ N\ uptake \\ & - Milk\ N + Meat\ N \end{aligned} \tag{3}$$

2.2.2.4. Box 4 Manure storage

Box 4 quantified N losses due to volatilization in animal stables and storage. The N inputs to this box were from total gross manure, while the N outputs were manure and volatile losses in stables and storage. As different loss factors apply for manure from indoor housing or grazing, the time ratio indoors:pasture was calculated and applied to the total amount of manure. For grazing, total N losses were quantified at a flat rate of 75% according to DüV (2017). With regard to indoor housing, losses were quantified at a flat rate of 15% in accordance with StoffBilV (2017) and DüV (2017) and subtracted from Box 4, due to leaving the system. Thus, Box 4 provided an approximation of the amount of N from manure available after deduction of losses (equation (4)):

$$\begin{aligned} Manure\ N\,[storage] = {} & (Manure\ N \times Ratio\ pasture \times N\ losses\ [outdoor]) \\ & + (Manure\ N \times Ratio\ indoor \times N\ losses\ [indoor_1] \end{aligned} \tag{4}$$

2.2.2.5. Box 5 Export

Box 5 quantified N exports of manure. The N inputs to this box represented manure in storage, and the N outputs were from manure and exported manure quantities (equation (5)). If a farm exported manure, this N amount was subtracted from the previously determined manure N quantity.

$$Manure\ N\,[post\ export] = Manure\ N\ [storage] - Manure\ N\ [export] \tag{5}$$

2.2.2.6. Box 6 Manure application

Box 6 quantified N losses due to field application. The N inputs in this box were from manure and the N outputs were manure as reported in NutC and application losses quantified at a flat rate of 15%, in accordance with StoffBilV (2017) and DüV (2017), subtracted from *Manure N [post export]*, leaving the system. The result was the calculated amount of N from manure applied to the field (equation (6a)). In the next step, this amount was subtracted from the quantity of manure taken from NutC, where losses in stables, storage, and application were also considered. As a result, balance 3 provided information on the difference between the amount reported in obligatory documentation and the calculated amount of N from manure applied on the field (equation (6b)).

$$\begin{aligned} Manure\ N\,[net] = {} & Manure\ N\,[post\ export] - Manure\ N\ [gross] \times Ratio\ indoor \\ & \times N\ losses\ [indoor_2] \end{aligned} \tag{6a}$$

$$\mathit{Balance}\ 3 = \mathit{Manure}\ N\,[\mathit{net}] - \mathit{Manure}\ N_{\mathit{NutC}}\,[\mathit{net}] \tag{6b}$$

2.2.2.7. Box 7 Total N balance

Nitrogen losses were added together (equation (7)) by combining balances 1, 2, and 3 and adding losses. This resulted in on-farm total gross N balance, generally expressed in relation to area for better comparability, primarily per hectare of utilized agricultural area (UAA) (equation (8)). This approach can be applied in terms of the available data and internal flows depicted in figure 1. Otherwise, the general equation is shown in equation (9).

$$\begin{aligned}\mathit{Losses} &= N\ \mathit{Losses}\ [\mathit{outdoor}] + N\ \mathit{Losses}\ [\mathit{indoor}_1] \\ &\quad + N\ \mathit{Losses}\ [\mathit{indoor}_2]\end{aligned} \tag{7}$$

$$\mathit{Total}\ N\ \mathit{balance} = \mathit{Balance}\ 1 + \mathit{Balance}\ 2 + \mathit{Balance}\ 3 + \mathit{Losses} \tag{8}$$

$$\begin{aligned}\mathit{Total}\ N\ \mathit{balance} = {} & \mathit{Purchased\ feed}\ N\ \mathit{intake} \\ & + N\ \mathit{fertilizer\ and\ manure\ import} - \mathit{Milk}\ N \\ & - \mathit{Meat}\ N - \mathit{Harvest}\ N\ \mathit{sold} - \mathit{Manure}\ N\ \mathit{soldexport}\end{aligned} \tag{9}$$

Figure 1 illustrates the methodological approach for SFA at farm scale applied in the present study. Rectangular boxes depict the N flows as defined above, circles are used to show stock changes for roughage and concentrates, and the rounded rectangle depicts the 'pasture system'. Balances are presented as scattered lines indicating N surpluses.

2.3. Nitrogen use efficiency

NUE was calculated at different levels (feed, field, farm). NUE is generally defined as N output divided by N inputs. The NUE at different levels was calculated as follows:

$$\mathit{Feed} - \mathit{NUE}\ [\%] = 100 \times \frac{\mathit{Milk}\ N\ [g\ DC^{-1}\ d^{-1}]}{\mathit{Feed}\ N\ \mathit{intake}\ [g\ DC^{-1}d^{-1}]} \tag{10}$$

Feed-NUE (equation (10)): For better comparability, only milk N was included as an output in feed-NUE, following Powell *et al* (2010) and Gourley *et al* (2011a). This approach is preferable, since the feed composition of dairy cattle is more reliable than that for young cattle in different development stages. Feed rations may also vary during the year or over a period of time. In the present study, average on-farm feed rations for dairy cattle were calculated based on multi-year records on feed rations, assuming that animals on the same farm are fed similar feed rations throughout the year and over the years.

$$\mathit{Field} - \mathit{NUE}\ [\%] = 100 \times \frac{N\ \mathit{uptake\ by\ crops}\ [kg\ a^{-1}]}{N\ \mathit{applied}\ [kg\ a^{-1}]} \tag{11}$$

Field-NUE (equation (11)): Harvested N amounts were taken from IRR. As inputs, N in manure (calculated according to equation (3)), mineral fertilizer, and BNF were taken into consideration, following Powell *et al* (2010). Nitrogen from manure on pasture was subtracted beforehand from the total manure N pool. For this, the ratio of pasture time to indoor time was calculated based on internal documentation on pasture management, and related to the total amount of manure derived from on-farm feed rations and animal products sold (milk, meat). Additionally, harvested N and manure N amounts from two different data sources (IRR, NutC) were taken into consideration as variant calculations (cf 2.4).

$$\mathit{Farm} - \mathit{NUE}\ [\%] = 100 \times \frac{\mathit{Milk}\ N\ [kg\ a^{-1}] + \mathit{Meat}\ N\ [kg\ a^{-1}] + \mathit{Harvest}\ N\ \mathit{sold}\ [kg\ a^{-1}] + \mathit{Manure}\ N\ \mathit{soldexport}\,[kg\ a^{-1}]}{\mathit{Purchased\ feed}\ N\ \mathit{intake}\ [kg\ a^{-1}] + N\ \mathit{import}\,[kg\ a^{-1}]} \tag{12}$$

Farm-NUE (equation (12)): On farm level, total N exports were divided by total N imports. For exports, all animal products sold (milk, meat, manure) and plant products sold (total harvest N except grass and maize) were considered. In the denominator, the sum of N imports in feed, mineral fertilizer and manure was considered, as well as ATD and BNF. Here, purchased feed N intake was calculated from the average on-farm feed ration.

Since dairy farms are normally analyzed as a whole, farm-NUE was of particular interest in this study. However, feed-NUE and field-NUE provide important information for a better understanding of farm management structure and the implications for N use.

2.4. Plausibility check of N-related data

To obtain comprehensive and reliable data, different data sources for harvested N and manure N amounts were taken into consideration in this study. Declarations in the NutC were compared with IRR data, feed rations and estimated N uptake through pasture grazing, and calculated values for manure N using SFA equation (3).

N quantities in declared roughage yields are much higher in NutC compared to IRR values, ranging from 21% higher for group 4 to 105% higher for group 2. They also greatly exceeded the N amount fed according to farm-individual rations plus estimated pasture intake. This discrepancy is presumably because farmers report roughage yield as an approximation, rather than a precise measurement, since roughage is predominantly utilized within the farm and not sold. Also, roughage rests and losses, as well as stock changes, may explain the discrepancy between roughage yields and rations. Roughage rests are normally returned to crop- and grassland, however, these flows are not accounted for in NutC. Therefore, declared gross roughage yields are rather overestimated on average, leading to an overestimation of N outflows from the field.

Compared to NutC declarations according to DüV (2017), calculated N from manure based on SFA is similar for young cattle including calves (+1.6 kg N/LSU/year) and consistently higher for dairy cattle (+24.5 kg N/LSU/year), over different production systems. Farms in group 1, 2, and 4 showed predominantly higher SFA values compared to NutC, while the deviations for farms in group 3 were both positive and negative to a similar extent. Obviously, N in manure is often underestimated in the NutC declarations. Further, the relation of declared roughage yields and manure N in NutC is not balanced when applying SFA equation (3), which reflects the balance of N inputs and outputs in the livestock production system, and thus appears implausible.

Figure A1 is available online at stacks.iop.org/ERC/2/105002/mmedia depicts deviations between the aggregate of N in roughage ration plus N uptake through pasture grazing minus manure N according to SFA, and roughage N minus manure N according to NutC. The aggregate values are on average much lower for SFA compared to NutC, showing that NutC values systematically distort the relation of N inputs and outputs in the field balance, due to underestimated inputs and overestimated outputs of the field balance. NutC data on roughage and manure N thus are not reliable to calculate field-NUE. In table A1, results of an explorative calculation of field-NUE using NutC data with low data reliability, and SFA data with high data reliability are presented. Field-NUE values based on NutC are by orders of magnitude higher compared to those based on SFA data, with maximum values above 100% in farms with grazing, and also the ranking of field-NUE per farm group differs compared to results based on SFA. The example shows the importance of robust and reliable data for NUE calculations.

For the analysis of N balances and NUE, data from NutC on input of mineral fertilizers, purchase and sale of organic fertilizers, yields of cash crops, and number of livestock and land area are used, as well as information on milk production according to monthly milk performance tests. As a result of the plausibility check, instead of inconsistent NutC data, yearly on-farm feed rations collected by the Chamber of Agriculture, data on roughage production from IRR, and calculated N uptake through pasture grazing and manure N according to SFA and manure N according to SFA equation (3) are used for the analyses of N balances and NUE.

2.5. Statistical analysis

For explorative data analysis, mean and standard deviation according to group affiliation were calculated based on the corresponding functions in *Microsoft Excel Professional Plus 2010.* The software SAS (*SAS 9.4*), commercial statistics software, was used in statistical analyses for independency. Kruskal-Wallis one-way analysis of variance (ANOVA), also known as the Kruskal-Wallis test by ranks, was applied to mean values of farms in group 1 and group 4. This is a commonly used test to investigate whether more than two independent samples are significantly different.

3. Results and discussion

3.1. Farm structure

The 30 dairy farms in the sample differed in structure both between groups and within each group (see table 1). Across all farms, total agricultural land area was rather similar (115 ± 46 ha; mean ± standard deviation), with differences mainly in the relative proportions of arable land and grassland.

With regard to structural features such as livestock density, size/ratio of grassland and arable land, and herd size, the 30 selected farms in Lower Saxony represented the diverse range of production characteristics in dairy farming in the region. Livestock density across all farms ranged between 1.1 and 3.0 LSU ha^{-1} (1.9 ± 0.4 LSU ha^{-1}), with an average total number per farm of 135 ± 52 LSU. This is relatively high compared with the German average and the European average (1.1 and 0.8 LSU ha^{-1} UAA, respectively, in 2016) (Eurostat 2019b).

Under EU regulations on organic production and labeling of organic products, farms complying with organic production rules must keep livestock density below 2 LSU ha^{-1} in order to avoid exceeding the European threshold value for manure application of 170 kg ha^{-1} (European Commission 2008). For conventional farms, there is no area-related limitation on livestock density. For dairy farms in Germany, Scheringer (2002) found that organic farms have higher NUE than conventional farms and that extensification and organic farming are effective measures to reduce N surpluses and improve NUE. However, lower livestock

Table 2. Comparison of nitrogen (N) inputs and N outputs on field level on farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing).

		N input [kg N/ha]					N output [kg N/ha]		
		Mineral fertilizer	Manure (gross)	Manure (net)[a]	Manure export	Manure import	Grass	Maize	Other crops[b]
Group 1	Mean	178	224	119	13	0.4	91	11	44
(n = 7)	Min–max	76–254	156–300	87–148	0–35	0–1	52–142	0–22	0–148
	SD	60	53	23	14	0.4	30	9	67
	Median	186	225	129	6	0.3	91	12	0
Group 2	Mean	113	209	128	28	18	89	18	15
(n = 8)	Min–max	54–144	174–243	105–151	0–112	0–104	43–115	0–42	0–52
	SD	29	29	18	40	36	27	17	20
	Median	122	217	132	10	1	96	12	4
Group 3	Mean	151	216	137	19	29	110	45	13
(n = 10)	Min–max	93–222	154–273	96–174	0–92	0–251	80–145	12–87	0–69
	SD	37	44	28	30	78	20	23	22
	Median	148	219	137	5	1	103	46	2
Group 4	Mean	118	236	165	33	29	116	64	44
(n = 5)	Min–max	78–176	153–353	107–247	0–92	0–61	56–164	17–158	0–103
	SD	40	73	52	37	29	39	55	52
	Median	101	216	151	24	27	119	53	15

[a] Including losses due to N emissions from volatilization in stables houses and storage (15%), during application to soil (15%) and from manure on pasture (75%).

[b] Harvested N except grassland and maize (e.g., oats, rape).

density does not necessarily lead to higher resource use efficiency or sustainability. For instance, Broom *et al* (2013) showed that livestock density of more than 4 LSU ha^{-1} in silvopastoral systems can result in high livestock production, while meeting to objectives of sustainability, biodiversity, and welfare for animals.

3.2. N input-output flows

Table 2 shows annual total N input and N outputs for farm in groups 1–4. Manure was the main N input source for all groups on average. Compared with available manure N amounts (excluding losses), mineral fertilizer was the main N source for farms in group 1 (60%) and 3 (52%). Group 2 and 4 farms used more N from manure (53 and 58 %, respectively) than from mineral fertilizer (47 and 42%, respectively). The area-related mineral fertilizer input differed greatly, ranging from a maximum of 178 ± 60 kg N ha^{-1} (group 1) to a minimum of 113 ± 29 kg N ha^{-1} (group 2). Available manure N was also a major N input source for which an increasing trend from group 1 (119 ± 23 kg N ha^{-1}) to group 4 (165 ± 52 kg N ha^{-1}) was observed. A similar trend was seen for gross manure N amounts, but the difference between the groups was smaller, ranging from 209 ± 29 kg N ha^{-1} in group 2 to 236 ± 73 kg N ha^{-1} in group 4. This is attributable to the high N losses from manure on pasture (75%), so that the gross values were reduced by just under half for groups with pasture grazing. For mineral fertilizer N ($p = .088$), manure N ($p = .570$), and available manure N ($p = .935$), no significant differences in trends were identified.

Manure imports and/or exports were observed on 19 of the 30 farms. On farms in groups 2 and 4, the amounts were similar but double the amount on farms in group 1 (13 ± 14 kg N ha^{-1}), considering the total sample size. Farms in all groups with manure imports had at least 18 kg N ha^{-1} on average, with the exception of group 1 (0.4 ± 0.4 kg N ha^{-1}). BNF was assigned to manure in the present study, but plays a small role in total N input. Based on farm-specific estimates of harvests and crop-specific parameters, only one farm in group 2 stated BNF in grain legumes. Generally, no BNF is expected on specialized dairy farms due to the high intensity of grassland management (Stein-Bachinger *et al* 2004).

Also N outputs are depicted as N flows per average farm hectare, so the N uptake per crop does not indicate yields per hectare but the share of total N flows per hectare of total UAA (ha), considering the total sample size. Farms in group 4 showed the highest N output from grassland (116 ± 39 kg N ha^{-1}) and the highest N output from maize (64 ± 55 kg N ha^{-1}) among all the groups. For maize, an increasing tendency from group 1 to group 4 was observed ($p = .012$), while no clear trend was noted for grassland or other crops. There were some similarities in the distribution of N outputs: on farms in all groups, grass from grassland was the main N output, followed by maize and other crops. An exception was observed for farms in group 1, where N yields with maize and with grass were smaller than with other crops. Due to the fact that the yields differed greatly related to total

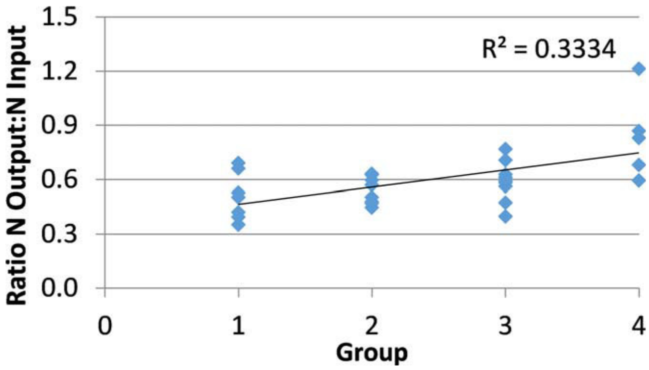

Figure 2. Ratio of all nitrogen (N) outputs (including harvest and animal products sold) to N inputs (including mineral fertilizers, gross manure, biological N fixation, atmospheric deposition) on farms in group 1 (full grazing) to group 4 (zero grazing).

UAA and that the 18 forage production farms included in the sample cultivated other crops than grassland and maize (rapeseed, oats, wheat, barley, rye, and others), different cultivation systems and crop mix were detectable.

The gross N output:input ratio on average of the groups increased slightly from full grazing to zero grazing management (figure 2): 0.51 ± 0.13 (group 1), 0.54 ± 0.07 (group 2), 0.59 ± 0.11 (group 3), and 0.84 ± 0.24 (group 4). Groups 1, 2, and 3 showed similar mean values and similar variations, while group 4 showed higher mean values, but also greater variation. A ratio >1 was only observed in group 4 (1.21). The trend of an increasing N output:input ratio from group 1 to group 4 was significant ($p = .019$).

In addition, it was observed that annual purchases of concentrates exceeded the amount of concentrates fed annually. Therefore, the concentrate stock was estimated for each farm and the concentrate intake was based on the daily feed ration following farm-specific data. An increase in concentrate feed N intake per LSU and year was observed from intensive grazing (group 1) to zero grazing (group 4). Group 4 farms showed the highest concentrate feed N intake (73 ± 16 kg N), followed by group 3 (53 ± 17 kg N), with group 1 (49 ± 6 kg N), and group 2 (47 ± 8 kg N) at a similar level. The difference between group 1 and group 4 was significant ($p = .012$). This shows that indoor systems with zero grazing seem to rely to a higher extent on concentrate feed, although they are known to be better at planning and adjusting feed rations (Powell *et al* 2010) and thus should have better conditions to utilize roughage efficiently.

'Pasture system' was considered as a separate sub-system in this study, as the exact proportion of pasture area was unknown and pasture uptake provided only an approximation. The mean over-/undersupply of N on pasture, taken as the difference between manure N on pasture and pasture uptake, was −21.7 ± 16.3 kg N ha^{-1} grassland for all farms with a pasture grazing system. This potential undersupply can be compensated for by soil N stock, diffuse N sources such as ATD, or even additional mineral fertilization not reported in NutC.

3.3. Total N balances and farm-NUE

Table 3 presents the mean, standard deviation, minimum and maximum values, and median of total gross N balances and the different types of NUE for farms in group 1 to group 4. Farms with intensive pasture management (group 1) had a total average annual surplus of 256 ± 83 kg N ha^{-1}, followed by group 2 (223 ± 28 kg N ha^{-1}), group 3 (239 ± 28 kg N ha^{-1}), and farms with zero grazing systems in group 4 (179 ± 38 kg N ha^{-1}). The range (min-max) was 162–380 kg N ha^{-1} for group 1, 182–267 kg N ha^{-1} for group 2, 137–477 kg N ha^{-1} for group 3, and 123–212 kg N ha^{-1} for group 4. The mean values showed a decreasing tendency in N surplus from the full grazing to zero grazing systems, with the exception of group 3 farms, but the differences between group 4 and each group with pasture grazing was more than 19%. Even though these differences were evident, they were statistically not significant ($p = .062$). For farm-NUE, no trend was observed. Group 3 farms showed the lowest farm-NUE (32 ± 9 %), followed by farms in group 1 (40 ± 15 %) and group 2 (43 ± 18 %). The highest farm-NUE was observed for group 4 farm (50 ± 23 %). The differences between groups were not significant ($p = .372$).

The average total gross N balance for all 30 farms at farm level was 228 kg N ha^{-1}, with an average farm-NUE of 40%. This value is similar to that in reported by Kelm *et al* (2007) for eight conventional dairy farms located in the Schleswig-Holstein region of Germany, which had an average farm-NUE of 34%. That study included full-grazing farms and zero grazing farms, and found that N balance and NUE did not differ greatly between these systems. Akert *et al* (2020) also observed an increase in (net) farm-NUE for commercial dairy farms from full-grazing to part-time grazing with substantial concentrate feed input. In contrast to the present study, the total N-balance raised as the use of concentrates increased. This may be because all farms in the present study fed considerable amounts of concentrates and farms in group 4 purchased considerably less mineral fertilizer

Table 3. Key data on total nitrogen (N) balance and different types of nitrogen use efficiency (farm-, field- and feed-NUE) on farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing). Mean, standard deviation (SD), lowest value (Min), highest value (Max) and median (n = 30) for the reference year 2014.

		Balance total [kg N/ha]	Farm-NUE [%]	Field-NUE [%][a]	Feed-NUE [%]
Group 1	Mean	256	40	46	22
(n = 7)	Min–max	162–380	27–61	26–66	18–27
	SD	83	15	16	3
	Median	233	34	38	21
Group 2	Mean	223	43	40	23
(n = 8)	Min–max	182–267	20–77	33–52	20–25
	SD	28	18	7	2
	Median	223	39	39	22
Group 3	Mean	239	32	47	25
(n = 10)	Min–max	137–477	20–48	32–69	19–30
	SD	94	9	10	4
	Median	210	33	46	26
Group 4	Mean	179	50	58	27
(n = 5)	Min–max	123–212	29–89	45–74	23–34
	SD	38	23	11	4
	Median	196	46	58	27

[a] Harvested N amount according to Internal Roughage Reporting, manure N amount according to on-farm calculation based on substance flow analysis (SFA) equation (3).

(table 3) than group 1. Indoor manure collection may result in a more extensive collection and, thus, in a higher degree of manure utilization. Quemada *et al* (2020) investigated the effects of externalized N inputs on NUE of agricultural farms in EU countries. For that, N losses for production of imported concentrate were considered (NUE from 25 to 75 %) whereas farm-NUE decreased by up to 15%, depending on country and farm type. In this study, we suppose that the consideration of externalities should include both import of concentrates and exported manure amounts. For this, farm-NUE including NUE for purchased concentrates and exported manure was calculated (table A2). We found that both factors can play an important role depending on their occurrence and magnitude at farm level. If external systems reach a high N use efficiency, our results are supported even when considering externalities. Inefficient external systems flatten the results so that trends are no longer recognizable. According to the system boundaries set, modifications need to be done with regard to calculation (Powell *et al* 2010) and assessment of NUE values (EU Nitrogen Expert Panel, 2015).

The EU Nitrogen Expert Panel (2015) developed a simple 'traffic light' indicator scheme based on Brentrup and Palliere (2010) for mixed crop-livestock systems differentiated according to livestock density. According to this scheme, a farm-NUE over 60% (for 2 LSU ha^{-1}) and 80% (for 1 LSU ha^{-1}) indicates soil mining; while a value less than 20% and 30%, respectively, indicates a high risk of N losses. Based on this, 47% of farms in the present study were within the optimum range, with NUE from 30 to 60 %. Farms in group 3 were on average at the lower limit with 32 ± 9 %, close to a risk of N losses, and group 4 farms were on average at the upper limit with 50 ± 23 %, close to a risk of soil mining. However, the EU Nitrogen Expert Panel (2015) points out that the proposed target values are tentative, with fluid boundaries.

Nitrogen surpluses reported previously by Gourley *et al* (2011b) for different dairy production systems fell within a wide range, from 47 to 600 kg N ha^{-1}, while farm-NUE ranged from 14 to 50 % (n = 41). In the present study, the range was slightly more moderate for both, with N surplus varying from 123 to 477 kg N ha^{-1}and farm-NUE from 20 to 89 %. The lowest N balance and the highest farm-NUE were found for farms in group 4, possibly due to a better targeted feeding, high amounts of manure for application accompanied by below-average purchases of mineral fertilizers, and a positive trade balance with regard to manure (Export > Import) (Powell *et al* 2010). According to Scheringer (2002), management measures to improve NUE can be addressed on three levels: animals (feeding, performance, stock), excrement (housing, storage, application) and utilized agricultural area (fertilization, grazing, cutting, catch crops, N-efficient crops).

The total N balances indicate the environmental pressure by revealing sources of unutilized N, and thus N losses, within livestock farming systems. Environmental impacts, i.e., water quality, are not specified, but different NUE levels can be used as a proxy for potential environmental effects. For this, additional long-term data would be needed on harvesting quantities, the intensity of mechanization, and site characteristics, in particular climate and soil properties (Schulte *et al* 2006).

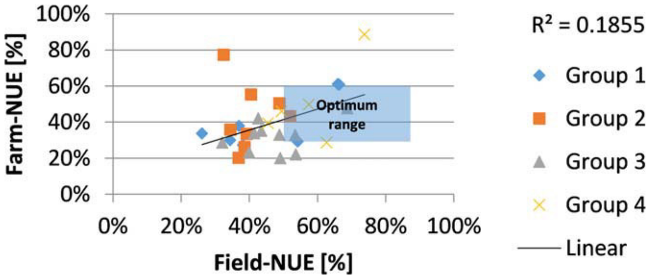

Figure 3. Relationship between field-nitrogen use efficiency (NUE) and farm-NUE of farms in group 1 (full grazing) to group 4 (zero grazing), based on data input from Internal Roughage Reporting (harvested N) and findings from substance flow analysis (SFA) (manure N).

3.4. Field-NUE

For field-NUE, the value varied from 40 ± 7 % (group 2) to 58 ± 11 % (group 4), with the other two groups showing average efficiency of 47 ± 10 % (group 3) and 46 ± 16 % (group 1). No uniform trend was seen and the differences observed were not significant ($p = .223$). It is worth mentioning that the group with zero grazing systems (group 4) had higher NUE at field level than all groups with pasture grazing. In pasture-based systems, a considerable part of manure is left on pasture and is lost to the surrounding environment to a greater extent. Therefore, in pasture systems, on average less manure is applied compared with in zero grazing systems. Thus, higher harvested N in zero grazing systems leads to more efficient N use at field level. Machmüller and Sundrum (2016) observed similar field-NUE for dairy farms in Germany, with an average of 58 ± 6 % without differentiating between pasture management systems. Differences may be due to the rather lower livestock density (1.3 ± 0.9 LSU ha^{-1}) and the associated lower amount of manure. According to the EU Nitrogen Expert Panel (2015), the optimal range is 70%–90% for field-NUE, or less strictly 50%–90%. Below 50%, there is a risk of inefficient N use and N losses, and also a risk of soil degradation and diminishing soil fertility, because nutrient uptake by crops and unavoidable N losses exceed the N amount applied to the soil (Brentrup and Palliere 2010). In the present study, only group 4 farms were in the optimal efficiency range. Group 1, 2, and 3 farms were on average below the threshold 50% level of efficiency and posed a risk of N losses. Efficiency-increasing actions should be taken if field-NUE remains at this low level over several years, including e.g., (technical) measures to increase N availability of manure in order to reduce total N inputs.

A positive relationship was found between farm-NUE and field-NUE (figure 3), i.e. as a tendency higher field-NUE are linked to higher farm-NUE. Only a few farms from each group were located in the optimum range (blue shaded area in figure 3) and thus farms from all groups need to improve their NUE, especially on field level.

For comparison, in 2014 field-NUE in Germany was around 64%, slightly above the average of the 28 EU member states (62%) and behind Romania, with the highest efficiency (90%). From 2004 to 2014, an increase in field-NUE in most EU member states has been observed (Eurostat 2018).

3.5. Feed-NUE

Feed-NUE showed a slightly increasing tendency from intensive pasture farming towards zero grazing systems, with significant differences between the groups ($p = .028$). Group 1 farms showed the lowest feed-NUE (22 ± 3 %) and group 4 farms the highest (27 ± 4 %). These findings are in line with Powell *et al* (2010) and with Arriaga *et al* (2009), who found that conventional dairy farms in Spain with mean livestock densities of 2.1 LSU ha^{-1} had feed-NUEs of 19 to 32 %. According to Chase (2003), feed-NUE values between 20 and 25 % indicate potential for improvements, values of 25 to 30 % are most common, values between 30 and 35 % are above average, and feed-NUE greater than 35% is excellent. The results of the present study indicate potential for improvement especially for farms with intensive grazing (group 1).

A positive relationship was observed between farm-NUE and feed NUE (figure 4), i.e. as a tendency higher feed-NUE are linked to higher farm-NUE. Only one farm (group 3) was near the optimum range defined by Chase (2003) and EU Nitrogen Expert Panel (2015). Farms in all groups need to improve their efficiency in terms of feed-NUE, either by decreasing inputs (feeding) or increasing outputs (performance). With regard to the distributions within and across the groups, we see potential for improvement in every group. For instance, N-reduced feed is already established on the market. There is further potential for optimization for all groups,

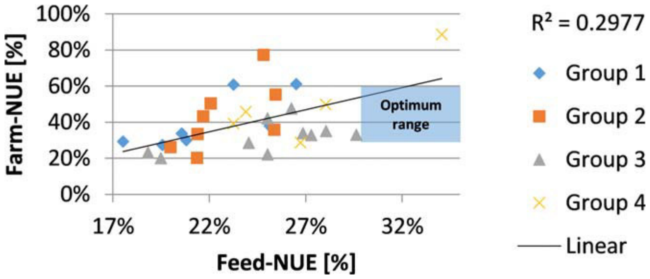

Figure 4. Relationship between feed-nitrogen use efficiency (NUE) and farm-NUE of farms in group 1 (full grazing) to group 4 (zero grazing).

particularly by means of digitization, and automated and individual feeding systems that respond to the nutritional needs.

Use of different methods in quantification of outputs makes comparability more difficult. While feed-NUE in most studies refers to milk as the only output, some approaches also include meat (Kelm *et al* 2007) and manure as a valuable product (Uwizeye *et al* 2014).

3.6. Overall NUE assessment

Farms in group 4 had the highest NUE on all levels, i.e., optimum farm-NUE and feed-NUE and field-NUE close to the optimum range. Also, the average total N balance for group 4 farms was far lower than for farms in the other groups. The ideal case of relatively high nutrient efficiencies and relatively low N surpluses was identified (Eurostat 2018), and the N outputs in harvested products were largely consistent (table 3). This supports findings in several explorative studies and farm analyses which indicate that N balance can be decreased while NUE remains constant or increases (EU Nitrogen Expert Panel, 2015). It also supports findings that farm-NUE in zero grazing systems is generally higher than in pasture-based systems, probably due to more precise and timelier information on the nutritive value of feed, so that the total feed mix can be better tuned (Daatselaar *et al* 2015, Powell *et al* 2010). For pasture-based systems, optimization of rations is hampered by varying pasture quality and differences in intake between seasons and farms (Jacobs and Rigby 1999). Therefore, we found indications supporting H1, as the N indicators investigated differed depending on the grazing system, although most differences were not statistically significant.

In this study, N balance and NUE were analyzed based on one year of data only. Multi-year data are available for purchases and sales of mineral fertilizers and manure, and for concentrate feed rations on certain farms. These data appeared to be rather unchanging, so that N balance and NUE can be considered rather constant and robust over time, which in turn leads to a more precise calculation of respective NUEs. However, 2014 was a good year for farming in Germany due to a mild winter and early onset of the growing season, resulting in German grain harvest, including grain maize, reaching a new record of just under 52 million tons (+11% on the six-year average) (BMEL 2014). Similarly, high grain yields cannot to be expected as the long-term average, so high yield levels need to be considered while interpreting the findings of this study. Moreover, if data are available, it is advised to calculate NUE and N balance over several years for better representation of the average situation.

The present study also showed the impact of data reliability and system boundaries set in analysis on field-NUE values. Farms with roughage production, particularly farms with a pasture-based management system, are more likely to be affected by data inconsistencies regarding farm-internal flows than farms cultivating cash crops. As shown in this study, quality of the data must be considered and plausibility must be checked in order to obtain robust results. Thus, we regard H2 as confirmed.

4. Conclusions

Analysis of farm N balances and NUE on different levels, based on substance flow analysis of N in different dairy farming systems in northwestern Germany, revealed indications of environmental pressure due to N losses. Potential for improvement in NUE in groups of farms with systems ranging from full grazing to zero grazing was identified, and should be pursued. Zero grazing systems show higher farm-NUE compared to grazing systems which can be attributed to more precise fertilizing and feeding management. The proportions of arable land used for grass, maize, and other cash crops did not have any marked impact on farm-NUE, but farms with a high proportion of N from cash crops showed high NUEs on farm-, field- and feed-level.

Total N balance decreased from full grazing to zero grazing, accompanied by an increase in farm-NUE and feed-NUE. On field level, higher efficiency was identified for zero grazing farms. Thus, the results can be used for benchmarking dairy farms in the study region. However, farm-NUE varied greatly between farms within groups. Thus, there is large scope for improvements without change of grazing management, or even switching to zero grazing.

Manure N and roughage N amounts are associated with high uncertainty when converting farm data into key figures, and both are frequently estimated from standard values. Here the amounts were calculated using detailed internal data, revealing discrepancies with values in farm data reporting. This finding needs to be taken into consideration in order to avoid systematic over- or underestimations of field balances and field-NUE. Therefore, farm-specific SFA can be used both to check data robustness and as a disaggregated flow analysis approach to identify N loss zones. As this is also an important finding for control authorities, plausibility checks based on SFA should be considered for further activities. If statutory NUE reporting is introduced as a complement tool to N balance, the key role of accurate N flow data should be considered by policymakers. More accurate documentation of feed imports and composition could enable the identification of N inefficiency hotspots. Otherwise, unidentified N surpluses can circulate in the system (e.g., as soil stock) or be lost as emissions (e.g., NH_3), while N inefficiencies remain constant at farm level as long as the sums of N inputs and N outputs do not change. An increase in NUE can only be achieved by increasing the overall output or by reducing the overall input. However, the impact of changed NUE on N surplus and potential environmental pollution is uncertain. Thus, both NUE for benchmarking the performance of farm nutrient management, and nutrient balances, as indicator for potential environmental pollution are recommended.

In order to assess dairy farming system sustainability according to national/international goals, further key parameters (e.g., animal welfare, biodiversity, landscape function) need to be considered, in addition to the indicators analyzed in this study. Further investigations are also required to allow comparability across all agricultural production systems. Political instruments and regulatory approaches need to find appropriate ways to reduce widespread excessive N surpluses and simultaneously increase NUE in farming systems in Germany. International comparability and benchmark setting are currently hampered by lack of uniform methodology, which should be harmonized in future work.

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Appendix

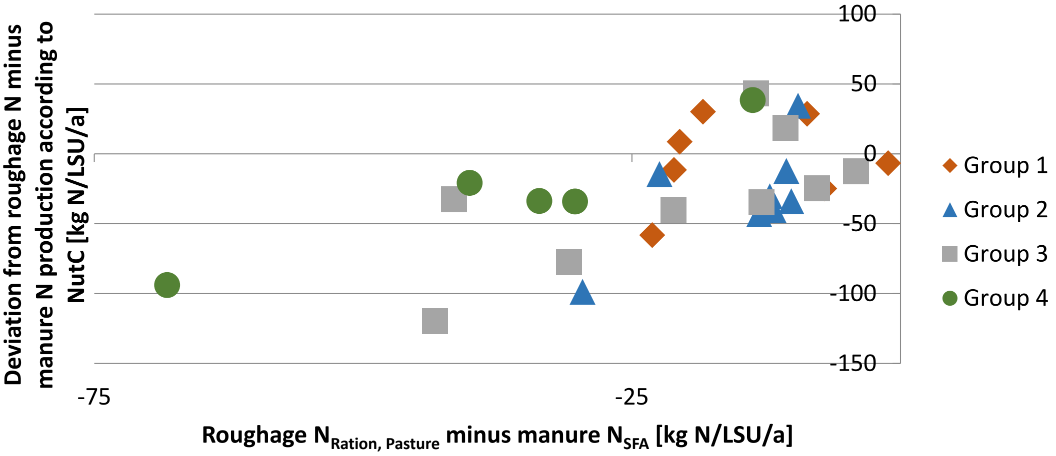

Figure A1: Deviation between on-farm roughage ration in Nitrogen (N), including N uptake through pasture grazing, and manure N according to substance flow analysis (SFA) and roughage and manure N according to Nutrient Comparison (NutC) (SFA minus NutC) for farms in group 1 (full grazing) to group 4 (zero grazing).

Table A1: Relationship between data reliability and nitrogen use efficiency (NUE) values on field level of farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing) according to different data sources. Mean, standard deviation (SD), lowest value (Min), highest value (Max) and median (n = 30) for the reference year 2014

		Data reliability	
		Low	*High*
		Field-NUE_{NutC} [%][1]	Field-NUE_{SFA} [%][2]
Group 1	Mean	90	46
(n = 7)	Min–max	72–136	26–66
	SD	22	16
	Median	81	38
Group 2	Mean	113	40
(n = 8)	Min–max	73–176	33–52
	SD	34	7
	Median	102	39
Group 3	Mean	82	47
(n = 10)	Min–max	48–124	32–69
	SD	22	10
	Median	84	46
Group 4	Mean	77	58
(n = 5)	Min–max	56–92	45–74
	SD	15	11
	Median	82	58

[1] Harvested N amount and manure N amount according to internal Nutrient Comparison (NutC).

[2] Harvested N amount according to Internal Roughage Recording, manure N amount according to substance flow analysis (SFA) equation 3.

Table A2: Nitrogen use efficiency (NUE) at farm-level under consideration of externalized N from purchased concentrates and exported manure with low and high assumptions on external NUE, based on findings in the present study, of farms in group 1 (full grazing), group 2 (half-day grazing), group 3 (partial grazing), and group 4 (zero grazing).

	Scenario	**Combined$_{low}$**[1]	**Combined$_{high}$**[2]
		Farm-NUE [%]	Farm-NUE [%]
Group 1 (n = 7)	Mean	28	33
	Min–max	16–50	20–56
	SD	15	16
	Median	23	27
Group 2 (n = 8)	Mean	24	30
	Min–max	16–33	18–43
	SD	6	8
	Median	23	29
Group 3 (n = 10)	Mean	20	25
	Min–max	11–37	13–43
	SD	7	8
	Median	20	25
Group 4 (n = 5)	Mean	28	37
	Min–max	18–46	24–60
	SD	11	14
	Median	24	33

[1] NUE of 50% is assumed for purchased concentrates, NUE of 15% is assumed for exported manure.

[2] NUE of 75% is assumed for purchased concentrates, NUE of 25% is assumed for exported manure.

6 Synopsis

This chapter consists of three sections. Firstly, generalizable findings from Papers I-III, as described in Chapters 3-5, are presented (section 6.1). Next, implications for policy advice are evaluated (section 6.2). Finally, limitations of the applied methods are discussed (section 6.3). In order to ensure consistency in meaning throughout the chapter, the N indicators investigated are defined below:

FarmB: Farm-gate nitrogen balance (gross), according to § 6 in combination with Annex 2 StoffBilV (2017).

SoilB: Soil surface nitrogen balance (net), according to §§ 8 and 9, in combination with Annex 5 DüV (2017).

FertP: Fertilization planning, according to § 4 in combination with Annex 4 DüV (2020).

NUE: Nitrogen use efficiency on different system levels (feed, field, or farm) following established practice (Powell et al. 2010).

6.1 Main findings from the research articles

Against a background of climate change, environmental pollution, and a growing world population, all human activities must focus on improving resource utilization. Optimized N management in farming activities is essential in order to minimize negative externalities (Erisman et al. 2008; Sutton 2011; Sutton & Bleeker 2013; Erisman et al. 2018). Regulatory approaches for achieving this, using agri-environmental N indicators for measuring, monitoring, and defining legal requirements, have been implemented, applied, and subsequently also overridden in German legislation (Dittert 2020; Latacz-Lohmann et al. 2021; Taube 2021).

The research in this thesis focused on comparison of these regulatory approaches in terms of selected criteria such as data reliability and data uncertainty, options for improving regulatory outcomes regarding N utilization and for identifying inefficiencies in N management on farm level, and the relevance of current N indicators and potential options for future N indicators.

In terms of methodology, the research mainly comprised:

a) Determining data reliability and data uncertainty by defining, assessing, and combining parameter-specific index-scores and variances.
b) Developing relevant N flows based on German Farm Accountancy Data Network (FADN) data and estimating N indicators embedded in German legislation for farm types based on EU farm typology.
c) Analyzing links between regional, farm structural, and socio-economic characteristics and N balance and NUE on farm level, using a robust multiple regression model.
d) Calculating NUE on the three system levels (farm, field, feed), based on detailed farm data, validated by substance flow analysis approach for dairy farms in a case study.

In terms of the methodological design employed in calculation of the N indicators investigated, the current regulatory framework was always used as a reference, wherever possible. In the following, the reasoning behind the chosen order of Papers I-III, the findings in the individual papers, and the context of the overall research are described.

Robust indicators are needed to set target values and ensure control and monitoring over time. As a first step in analyzing N indicators of nutrient management in Germany, the relevant regulatory approaches were identified, namely fertilization planning (FertP), farm-gate N balance (FarmB), and soil surface N balance (SoilB), formerly known as *Nutrient Comparison* (Dt.: "*Nährstoffvergleich*") (DüV 2017). Several studies have compared the design of N balances at different spatial and system scales (Bach 2013; Häußermann et al. 2020b; Quemada et al. 2020; Schulte-Uebbing et al. 2022; Zinnbauer et al. 2023), but that research did not cover FertP, possibly due to its more recent introduction and methodological heterogeneity. Farm-gate balance has been identified in multiple scientific studies as the most integrative and meaningful N indicator (Oenema et al. 2003; Schröder et al. 2004; Nevens et al. 2006; Schröder & Neeteson 2008; Bach 2013), but an analysis using appropriate criteria to assess robustness and address reduction requirements based on regulations has so far been lacking. This research gap was filled by Paper I, which assessed data reliability and data uncertainty. It also compared the design, purpose, data requirements, and strictness of regulatory approaches related to N management in Germany, by defining parameter-specific index-scores and variances, and by calculations based on comprehensive farm data (FADN). A key finding was that FarmB scored highest regarding data reliability and certainty, followed by SoilB and FertP. The high ranking for FarmB was mainly due to its receipt-based approach and because it does not consider farm-internal N flows, which are associated with lower reliability (e.g., fodder and forage produced and used on-farm) and higher uncertainties (e.g., digestate or animal excretion). As a result of this finding, FarmB was selected for more detailed analysis as a key indicator in the other studies. A previous study comparing N budgeting approaches with different system boundaries identified FarmB as having the lowest relative uncertainty (Oenema & Heinen 1999). FarmB also meets the criteria for selection of agri-environmental indicators defined by Schröder et al. (2004) to a great extent, e.g., in terms of responsiveness of actions, having an integral nature, and being efficient regarding costs for accurate data provision. Based on these criteria, FarmB is an effective and comprehensible assessment system, which is crucial for meaningful regulation and interpretation of the indicator values. The findings in Paper I provide guidance for policymakers in selection of appropriate indicators for achieving the targets set, and their implementation within legislation. However, the analysis also identified room for improvements, e.g., through uniform documentation of quantities and qualities of traded organic fertilizers, standardized documentation on nutrient content in fertilizers, feed, and forage, and improved methodology for estimation of BNF. In terms of FertP, which through the requirements in the Nitrates Directive is the primary approach for nutrient management in the EU (Klages et al. 2020b), there is reason to evaluate the crop-specific nutrient demand values set in DüV (Taube 2018). These values are particularly crucial for deriving crop- and site-specific N requirements, and thus the maximum fertilizer amount that may be applied. One issue that might arise is systematic overfertilization for several crop types, as the principle followed is to minimize the risk of yield losses, requiring values above which there is no further yield response to be set (Steinfurth et al. 2022).

Furthermore, Paper I contributed to establishment of a methodological framework (in the form of a statistical calculation program) for quantifying various N indicators based on German FADN, which comprises representative and comprehensive sectoral farm data provided by the BMEL. Previous studies have estimated N balances based on farm accounting data (Bach et al. 1997; Gamer & Zeddies 2006; Gamer & Bahrs 2010; Bach et al. 2011; Ehrmann 2017), but those approaches did not cover recent innovations within the FADN (e.g., consideration of mineral fertilizer amounts since 2016/17), did only partially focus on different farm types, and have not yet been applied to other N indicators, such as FertP or NUE.

The new methodological framework allows N indicators to be systemized and automatically calculated over time. Additionally, the impact of regulatory approaches and respective thresholds as defined in German legislation on farm-type level can be quantified and then allocated to the sectoral UAA. Through this, the statistical calculation program developed can be used for impact assessment of policy measures on farm level. Implementation of new N indicators into the calculation program is time-effective, due to the improved quantification of the most relevant N flows. At regional level, impact assessments of national policy measures relating to fertilizer application will soon be conducted through the impact monitoring of DüV to be enacted in 2024, which evolved from the AGRUM-DE joint research project (Schmidt et al. 2020; Zinnbauer et al. 2023).

Among the regulatory approaches investigated in Paper I, FertP had the most restrictive effect at sector level (10 kg N/ha UAA reduction requirement), followed by SoilB (9 kg N/ha) and FarmB (2 kg N/ha). At farm-type level, the highest reduction requirements were in FertP or SoilB. At sector level, however, the farm-individual maximum N surplus, which is optional for farmers to calculate according to § 6 StoffBilV (2017), was found to be the most restrictive regulatory approach. Based on all farms, the reduction requirement was about 13 kg N/ha, thus limiting N input more than the approach of a flat-rate threshold at 175 kg N/ha. However, threshold levels are normative definitions by policymakers, so targeted adjustments allow for higher restrictiveness and thus increased positive environmental impacts (Taube et al. 2020). To this end, advanced assessment systems for farm-gate N and P balances within StoffBilV to ensure sustainable and resource-efficient nutrient use are expected within a future amendment process, as further discussed in section 6.2.

On the basis of these findings, it was reasonable to use the statistical calculation program in Paper II to estimate NUE on farm level as an informative N indicator based on robust parameters, as a first step in NUE benchmarking for different farm types in Germany. FarmB, in which surplus or deficit is a pressure indicator with a preventive purpose, can be transferred into the performance indicator farm-NUE, as both are based on equivalent parameters (Powell et al. 2010; EUNEP 2015). Note that "efficiency" here does not refer to economic efficiency in terms of the monetary output/input relationship, but considers input efficiency in terms of the physical output/input relationship. By definition, efficiency improvements result in higher output per unit of input, with the regulatory framework serving as the system boundary.

The simultaneous analysis in Paper II provided insights into the contribution and coherence of both N indicators. Interestingly, the analysis revealed great variations within each farm type, indicating potential efficiency reserves. Specific focus was placed on farms with animals, as their N performance was found to be considerably lower than that of arable and permanent crop farms. In particular, the results showed that dairy farms, other cattle farms, and pig and poultry farms had mean values which were much higher than 70 kg N/ha for FarmB and lower than 60% for farm-NUE, meaning that the sustainability goals on sector level could be jeopardized (EUNEP 2015;

German Federal Government 2019, 2021a). The lowest N efficiency (44%, 0.455 StdMean) on farm level was found for dairy farms, while N surplus was higher for pig and poultry farms (135 kg N/ha, 3.067 StdMean) than for all other farm types (Paper II).

In addition, interrelations between regional, farm structural, and socio-economic characteristics and the two indicators investigated (FarmB and farm-NUE) were identified (Paper II). The results revealed significant effects of soil-climate areas and crop diversity on N performance. Crop selection also had significant effects, with maize and sugar beet making strong positive contributions to N efficiency, presumably due to good N supply from organic fertilizers, from the soil N pool and, in the case of maize, from N-rich biomass production (Amelung et al. 2018; Schubert 2018). Operating profits showed a positive interrelation with procurement of advisory services, confirming previous findings (Prokopy et al. 2008), indicating a need for wider provision of high-quality, agri-environmental-related consulting services. These findings can serve as a practical guide for policymakers seeking to develop targeted policy measures. Together with other results presented in this thesis, they also highlight the importance of considering different dimensions for policy design in order to improve N performance in the long term. In future studies, other factors beyond those studied here should also be considered, as stronger efforts and innovative approaches are needed to improve N utilization. Future work should include, in particular, the use of novel and enhanced technologies such as artificial intelligence-supported precision farming, monitoring techniques using drones and remote sensing, or washwater irrigation (Osterburg & Runge 2007; Flessa et al. 2014; Bonkoß et al. 2020). Management improvements are also needed, subdivided into *animals*, *excreta*, and *farmland* (Scheringer 2002), as specified in section 6.2. In terms of global food production and considering technological advances, there is great potential for closing N efficiency gaps (Wuepper et al. 2020; Zhang et al. 2022; Gao & Cabrera Serrenho 2023; Jain 2023).

Due to findings in Papers I and II on the crucial position of dairy farms with regard to highly varying N indicator values and low farm-NUE and high FarmB values, further in-depth analysis of dairy farms was carried out in Paper III. Substance flow analysis, which is reputed to be laborious and complex due to the amount of required farm data (Gerber et al. 2014), was used to provide a plausibility check and contributed more knowledge of the N flows. Calculations of N balance and NUE on different levels (feed, field, farm) based on comprehensive farm data that had been checked for plausibility provided a comprehensive picture of N management, N performance, and potential hotspots for N inefficiencies on dairy farms. In particular, differences were observed between and within grazing systems, where indoor systems (zero-grazing) systems showed the highest mean farm-NUE (50%) and feed-NUE (27%), while total N surplus was highest (256 kg N/ha) for full grazing farms. A similar trend was observed when considering the effects of externalized N losses such as imported concentrates or exported manure amounts, as demonstrated previously (Quemada et al. 2020). This may be attributable to more precise information on feeding quantities and qualities, and lower N losses, in zero-grazing systems (Jacobs & Rigby 1999; Powell et al. 2010). Levels of variation and efficiencies on different scale were similar to those reported in other studies on German dairy farms (Kelm et al. 2007; Machmüller & Sundrum 2019). Overall, the approach used in Paper III proved to be appropriate for identifying internal N flows and potential losses, and thus for deriving targeted measures to improve the N performance of dairy farms with different grazing systems. Farm managers in particular can benefit by identifying N efficiency reserves and exploiting these in order to save costs, either due to relative reductions in input quantities (e.g., improved feeding and fertilizer management) or to increases in output (e.g., increased animal performance, manure exports due to efficient fertilizer management). This is especially the case if validated data are used, as shown in this thesis. Identification of inaccuracies in reporting based on default values from regulations using substance flow analysis can enable control authorities to proceed more effectively and efficiently, which is seen as a main pillar for assessing environmental strategies focusing on N (Scheele et al. 1993).

6.2 Implications for policy advice

The findings in this thesis can help policymakers identify and apply appropriate indicators for N legislation. Improved N utilization is addressed in numerous national and international climate, environmental, and sustainability frameworks, so policymakers need robust indicators that provide trustworthy information, based on reliable data, to define indicative target values. Identification of determinants of N indicator values can also contribute to formulation of targeted policy measures that support the necessary transition towards more sustainable agriculture. Robust indicators are equally important to ensure monitoring and control over time. The FarmB approach (and indicators based on equivalent parameters) showed a high degree of data reliability and data certainty. Therefore, requirements based on such indicators are relevant to counteract harmful environmental effects targeted at national level (e.g., German Sustainable Development Strategy, Climate Action Program 2030), EU-MS level (e.g., EU Sustainable Development Strategy, Nitrates Directive), and global level (e.g., UN Sustainable Development Goals).

Initial N legislation in the EU was mainly designed to protect groundwater and surface waters (European Council 1991; Kuhnt 2017), but achieving the climate target set for Germany, namely climate neutrality by 2045, will necessitate further major N reduction efforts (German Federal Government 2021b). For the agricultural sector, the interim target is to achieve a greenhouse gas emissions reduction from 70 million t CO2-eq. in 2020 to 56 million t CO2-eq in 2030 (German Federal Government 2019). Three key areas for action with high reduction potential have been defined (Grethe et al. 2021), namely (i) improving N efficiency, (ii) reducing consumption of animal products, and (iii) rewetting peatlands. Reduction potential from fertilizer use of up to 4.5 million t CO2-eq has been estimated, due to two measures: (1) implementation of a robust, transparent, and controllable FarmB within German legislation regulating sustainable and resource-efficient N use (StoffBilV), and (2) introduction of an N tax on the consumption of mineral fertilizers.

Thus, a comprehensible and more stringent assessment system in StoffBilV is needed (Taube et al. 2020; Grethe et al. 2021; Löw et al. 2021). This includes a mechanism to contextualize the N surplus, in order to ensure sustainable and resource-efficient N utilization on farms, as stated in § 3 StoffBilV (2017), and help achieve the German climate and sustainability goals (German Federal Government 2019, 2021a). In a recent report submitted to the German Bundestag, different models for revising the assessment system were presented and analyzed by a group of scientific and administrative experts under the lead of the BMEL and BMUV (Löw et al. 2021). Three options intended to serve as a basis for the legislative amendment process were described and compared. These differ from the assessment system introduced with § 6 in combination with Annex 4 StoffBilV (2017), namely a flat-rate threshold of 175 kg N/ha or a farm-individual maximum surplus (with a potential degree of freedom to exceed by up to 10%). Unlike the current approach, the models described in the report are based on production and application of organic fertilizers (Löw et al. 2021).

There are major differences between the options (model 1-3) with regard to the level of gaseous N losses permitted (from animal stables, manure storage, and manure application), the level of the authorized area-related flat-rate surplus, and staggered tightening of the permitted maximum surplus. The mean N reduction requirement related to total farm area varies between 14 kg N/ha (model 1) and 19 kg N/ha (model 2 and 3) for the agricultural sector in 2030, applied on farming activities documented in FADN between 2016/17 and 2018/19 (Löw et al. 2021). In 2022, the amendment process was driven forward further when the BMEL leadership changed after elections from the Christian Democrats to the Green Party in the *Scholz-cabinet* since December 2021 (Agra-Europe 2022). The third model is likely to include the most constructive elements and may be intended to serve as the base, i.e., a two-tier assessment system with N loss factors based on Annex 2 and 3 of DüV (2020), and an area-related flat-rate surplus of initially 50 kg N/ha. It is limited upwards by the upper application limit for organic fertilizers of 170 kg N/ha defined in § 6 DüV (2020), in line with EU requirements in the Nitrates Directive. The distinction between potential gaseous N loss factors for (i) stables and manure storage and for (ii) manure application allows differentiated targeting of possible improvements in NUE, e.g., increased efficiency through modern technologies. Staggered tightening of permitted N losses over time is also considered sensible in order to ensure adaptation time for farms on the one hand, and to take account of technical progress on the other. A two- to three-tier system seems expedient in order to avoid overcomplicating the assessment system and keep acceptance high. However, stringent application of these factors based on national regulations (DüV 2017, 2020) allows very high (up to 240 kg N/ha) maximum N surpluses for farm systems utilizing solid manure. In order to circumvent this effect: (a) adjustment of the factors for solid manure to those for liquid manure would be possible, since no relevant differences in N surpluses between farms with similar characteristics utilizing solid or liquid manure have been found to date (Löw et al. 2021). This may be because plant-available N supply from solid manure is long-term, with less risk of leaching compared with liquid manure (LfL 2003). (b) An additional and general maximum N surplus threshold limit for all farms (including systems with solid manure) could be integrated (e.g., 140 kg N/ha), including a staggering mechanism.

The idea of a flat-rate threshold for all farms (and farm types) does not seem to be advisable. Even if the threshold is set far below 175 kg N/ha (e.g., at 120 kg N/ha), farm-specific characteristics are inevitably insufficiently considered by this approach. In addition, there are no incentives to increase efficiency for farms that still have a lot of scope for N utilization. These farms may even be tempted to exploit their scope further for economic reasons, for example by importing nutrients unnecessarily. Calculation of a farm-individual maximum N surplus according to Annex 4 StoffBilV (2017) needs to be focused, particularly since previous amendments to fertilization regulations seemed to follow the principle “as much as required”. If BMEL intends to enhance the existing assessment system with elements specified in the recent report (Löw et al. 2021), there are several aspects to be taken into account. First, the actual assessment system allows potential N losses for roughage storage at a rate of 10% of the harvested roughage. This percentage derives from a publication quantifying potential dry matter losses of up to 10% (Köhler et al. 2016). However, this magnitude is not applicable to N losses, which should be corrected and thus reduced in an amendment of the ordinance. Potential N losses due to volatilization in animal houses, in storage, and during application should also be considered. Currently, both standard factors and measurement results are utilized, so an urgent step is to further define the options for determining manure N content in order to quantify N flows in a more reliable way. A cascade of options would be conceivable here, e.g., starting with measurement results (e.g., by additionally defining measuring frequency, qualification of the sample taker, methodological and technical standards) or, if this is not possible, using default values. Plausibility checks based on N input amounts, as already anchored in the Technical Instructions on Air Quality Control (TA Luft 2021) and already used by the Bavarian State Research Center for Agriculture in a tool accessible for farmers (LfL 2022), should also be an option for farms. Since different N loss paths are considered in Annex 4, the degree of freedom to exceed the calculated maximum N surplus of 10% is questionable.

A recent political announcement by the current government (*Scholz-cabinet*) stated that Germany will further focus on StoffBilV, with FarmB as a relevant agri-environmental N indicator (Agra-Europe 2022). Thus, BMEL aims to develop a new assessment system to ensure sustainable and resource-efficient use of N on farms, and to effectively contribute towards the targets set in the Climate Action Program 2030 (German Federal Government 2019) and the German Sustainable Development Strategy (German Federal Government 2021a). At the same time, BMEL intends to establish an easy-to-understand and practical system that applies uniformly to all farms and is not more restrictive than the fertilization restrictions in DüV through implementation of the EU Nitrates Directive (BMEL 2020b, 2021). However, in order to increase the efficacy of this approach, sanctions must be linked to transgression of N surplus thresholds at farm level, with severe fines accompanied by mandatory participation in training courses and the obligation to report annual farm data on N flows and FarmB to the authorities responsible for fertilizer law.

As mentioned above, N taxation on mineral fertilizer consumption (e.g., 0.5 €/kg N) has been suggested as a further instrument to improve N efficiency (estimating an application reduction of around 11%) (Grethe et al. 2021). This type of economic instrument has already been frequently discussed in previous literature (Weingarten 1996; Schleef 1999; Osterburg & Runge 2007; Wüstholz & Bahrs 2013). A key advantage is that a tax is easy to impose and control, and besides an efficiency increase in mineral N fertilizer use it may also increase the value of organic fertilizers, which are likely to be utilized more efficiently. On the other hand, this instrument is rather untargeted, since no regional or management-specific differentiation is made (Barunke 2002; acatech 2023). A remedy could be a progressive tax rate, but this would make the instrument more cumbersome. Another instrument might be a levy on high surpluses (or reward for low surpluses), which would require more effort for implementation, especially when considering regional conditions, e.g., critical loads (Schulte-Uebbing et al. 2022; acatech 2023). This instrument is more targeted and could be easily integrated into a digital tool or register. The idea of taxing mineral N fertilizer is primarily based on the fact that such fertilizers were available at low cost in Germany in recent years and decades, e.g., around 0.8 €/kg N as a 20-year mean (BMEL 2022a). Since the beginning of the 2020s, prices for mineral fertilizers have risen sharply, by up to 200% by 2022 (BMEL 2022a; DESTATIS 2022; Uthes 2022). The main reasons are higher production costs and issues of accessibility in the short-term due to the Russian invasion of Ukraine. In the medium-term, energy costs are expected to remain on a medium to high level and price volatility for N fertilizers will continue (Uthes 2022). In the short-term, mineral N fertilizer consumption has fallen, even without N taxation. In general, a reduction in N fertilization through an increase in N input prices can only be expected if prices of agricultural sales products remain constant, fall, or increase less. If fertilizer prices and prices for agricultural commodities increase to the same extent, no change in the fertilization behavior of farmers can be expected, as recent studies show for cereals (Meyer-Aurich & Karatay 2019; Meyer-Aurich 2022).

In addition to an effective and robust regulatory framework, further measures are needed as part of a holistic approach to achieving a reduction in N surpluses in the food system. These include sustainable farming structures, knowledge transfer and technologies, suitable economic frame conditions, and sustainable consumption patterns.

A reduction in on-farm N balances can be achieved without reducing crop yields, in particular in situations with high N surpluses. A previous study demonstrated the positive effects of agri-environmental measures and water protection advisory services by comparing farms that benefit from both with reference farms located outside the designated areas for drinking water abstraction in Lower Saxony. Compared with reference farms, farms with water protection advice decreased net farm-gate N balances by 26 kg N/ha, calculated as two-year means, between 1998 and 2012. The reduction in mineral fertilizer quantities applied was at a similar level during that period, whereas the use of organic fertilizers slightly increased (Horstkötter et al. 2015). Overall, NUE increased due to reduced input and constant output quantities. These results were updated and validated in a later publication (NLWKN 2019). It has been estimated that reducing mineral fertilizer use in the agricultural sector to this extent would be sufficient for achieving the sustainability goal of 70 kg N/ha N surplus of the German sectoral N balance without a yield drop, due to efficiency reserves (Osterburg et al. 2019).

Results from the EU 7th Framework Program for Research project “ENVIEVAL” (Development and application of new methodological frameworks for the evaluation of environmental impacts of rural development programs in the EU) showed that N balances calculated by advisory services or other stakeholders may differ considerably from mandatory N balances according to DüV 2007. Regarding implementation of water protection advisory services, this means that on-farm N balances may worsen in the short term due to changed methodology and less individual discretion. This can be traced back to the fact that technical advice induces a bias, as N balances are calculated differently using more reliable data sources and/or are calculated more precisely (Balázs et al. 2015). Based on robust N indicators, however, positive effects can be observed for water protection advisory services (Horstkötter et al. 2015; NLWKN 2019). In addition to a reduction in N surpluses and an associated increase in NUE, effects such as greater environmental awareness and cost reductions are apparent (EUNEP 2015; Oenema & Korevaar 2018). In future, cooperative approaches and knowledge transfer are conceivable. Promising pilot projects on cooperative advisory formats have already been performed in some European countries, e.g., in Belgium (Flanders) farm managers interact regularly with other farm managers and administrative advisors (Vlaamse overheid 2022). Long-term approaches such as environmental education in schools and an agri-environmental focus in vocational and university education should contribute relevant know-how to a broad range of young farm managers.

The results in Chapter 3 of this thesis clearly showed that N fertilization is between 6 and 28 kg N/ha higher than required for all farm types according to § 4 DüV (2020), with mineral fertilizer being the major N input source for farms in Germany. More than 80% of agricultural sector N inputs come from mineral fertilizers and feedstuffs, as shown e.g., by calculations by Julius Kühn Institute in collaboration with University of Giessen based on national farm survey data (Löw et al. 2021). In order to lower mineral fertilizer application and increase N efficiency of organic fertilizers, a further approach might involve processing to allow for substitution of mineral fertilizers with RENURE (“REcovered Nitrogen from manURE”) products, in line with a circular economy, contributing to sustainability and climate goals. Manure processed in this way (e.g., by solid/liquid separation for raw manure) is characterized by similar N leaching potential and agronomic efficiency as synthetic mineral fertilizers (Huygens et al. 2020). RENURE products are currently classified and treated as organic fertilizers in the EU Nitrates Directive. In order to combat “volatile mineral fertilizer prices and close nutrient cycles”, COM discusses the use of RENURE products in compliance with the Nitrates Directive in the context of COM´s Integrated Nutrient Management Action Plan adopted in the beginning of 2023 (European Commission 2022a). The BMEL expects that RENURE products will no longer be classified as organic fertilizers in the future (then following the same regulatory provisions as for mineral fertilizers), and thus will be exempted from the upper application limit of 170 kg organic N/ha according to § 6 DüV (2020). This could be implemented through derogation for individual EU-MS, or by means of an amendment of the Nitrates Directive Annex III (BMEL 2022d).

In addition, the introduction of a regional, UAA-related, and ecologically responsible limitation of livestock density would have positive effects in reducing Germany´s N surplus, e.g., due to decreasing import pressure on feedstuffs. In principle, this restriction is already part of German legislation since 1998/99. In order to define whether an agricultural enterprise should be considered an agricultural farm or an industrial enterprise according to tax law, a degressive approach was followed, so that the maximum threshold was around 2.3 LSU/ha depending on the UAA to be considered a farm for taxation. Due to tax avoidance and the area-based upper application limit for organic fertilizers according to the amendment in DüV 2007, this regulation has lost some of its relevance (Klapp et al. 2011). There are still calls by political decision-makers from different parties for a tightening (e.g., 1.7 LSU/ha), and for defining a general threshold due to permitting procedures (embedded in Federal Emission Protection Law and Construction Law; Dt.: "*Bundesimmissionsschutzgesetz und Baurecht*") or within the German Fertilizer Law, in order to reduce the N pressure on the environment (Landtag MV 2012; MKLLU MV 2021). In addition to the N problem, livestock farming plays a major role in terms of biodiversity loss associated with land cover change and as a source of greenhouse gas emissions (Gao & Cabrera Serrenho 2023; Jain 2023). The inefficient rate of conversion of plant protein into animal protein is particularly critical, as 50-90% of N consumed by livestock is excreted as manure (Zhang & Lassaletta 2022). The so-called "*Borchert Kommission*", a competence network established in 2019 from the *Merkel III-cabinet* consisting of representatives of the federal administration, *Länder*-administration, associations, business, and science, argued against mandatory area-related livestock densities, as this would endanger German competitiveness with the world market, leading to welfare losses (Kompetenznetzwerk Nutztierhaltung 2020).

In this context, targets and implications of the Farm to Fork (F2F) strategy (COM/2020/381 final) should also be emphasized. The strategy aims to reduce losses of nutrients from fertilizers by 50%, resulting in a reduction in the use of fertilizers of at least 20% (European Commission 2022b). Using a modelling approach, a recent study analyzed potential effects of selected F2F and biodiversity strategy targets, as central parts of the COM Green Deal, in the framework of the 2030 Climate targets (Barreiro Hurle et al. 2021). The authors found a decreasing effect on N surplus, with a reduction of more than 33% on average for EU-MS. When making full use of the possibilities under the new CAP starting in 2023, the effects may even increase. This would imply effects beyond the German climate and sustainability goal for N surplus, if the benefits were to apply to all EU-MS equally. With respect to Germany, the calculated reduction is of a magnitude estimated previously for a reduction in N surplus and mineral fertilizer use (20-30 kg N/ha) that could be achieved through intensive water protection advice (Horstkötter et al. 2015).

NUE on farm level is another relevant N indicator (EUNEP 2015), and can be derived from the same parameters as FarmB with a high level of data reliability and data certainty, as demonstrated in Chapter 3 and 4 of this thesis. When designing future nutrient policies, it should nevertheless be kept in mind that N efficiency increases alone should not be the main aim, as they may lead (in particular in the longer run) to negative environmental effects (e.g., decreases in soil fertility) or to ultra-intensive agricultural systems. Therefore, links to regulatory law (in particular to the FarmB threshold values) and/or additional implementation of maximum N input quantities (a so-called "maximum fertilizer intensity", possibly subdivided into mineral and organic fertilizers) are recommended. Setting ranges of NUE levels to be aimed for, depending on farm type and farm structure, can be a useful aid in this respect. Improving NUE can be achieved by technological and management advancement in three domains (Scheringer 2002): (1) animal management (feeding, performance, stocking), e.g., by smart-feeding robots or N-reduced feeding, (2) excreta management (housing, storage, application), e.g., by automated collection and covering of manure or frequented and qualified analysis of manure N content, and (3) farmland management (e.g., fertilization, grazing, catch crops, N-efficient crops), e.g., by cultivation of catch crops and using precision farming techniques (Osterburg & Runge 2007; Flessa et al. 2014; Chmelíková et al. 2021). These management measures should be underpinned by fiscal incentive policy, e.g., through subsidy or funding programs, and driven by advisory or cooperative approaches, e.g., via joint businesses and ring networks. This may facilitate collective financing, acquisition, and use of high-tech farming equipment and knowledge transfer.

This thesis found that certain farm types particularly often fail to achieve sustainable farm-NUE levels, and therefore a specific analysis was performed on dairy farms. Such disaggregated analysis required the use of digital-based tools, as manual data processing was too time-consuming. Therefore, (mandatory) use of digital data repositories and software for data analysis is explicitly recommended, especially for farm types with complex farm structures and multiple nutrient flows. The tool for Annual Nutrient Cycling Assessment (short: ANCA-tool) established in the Netherlands, use of which is a requirement for access to the national milk processing industry, can serve as a model. It displays N flows and several N indicators, based on which efficiency reserves can be identified and attributed to the respective source (Aarts et al. 2015). From 2026 onwards, Denmark plans to introduce a mandatory digital tool that will allow calculation of N indicators (e.g., N balance) and of greenhouse gas emissions associated with agricultural activities, and will also enable benchmarking and suggest improvement measures autonomously (Christel et al. 2022). In general, a mandatory tool could help remedy the systematic errors and high temporal costs associated with documentation, to the benefit of both farmers and control authorities.

In Germany, similar efforts have so far only been undertaken in rudimentary form. It would be highly beneficial if existing pilots and practice tests were maintained and extended. The federal government of the *Scholz-cabinet* announced a digital nutrient register in the coalition agreement (SPD et al. 2021), but it has not yet been implemented (German Federal Government 2022; Agra-Europe 2022). The intention is combine the proposed nutrient register with the amended StoffBilV, the intended impact monitoring of DüV, and several approaches of the *Länder* (German Federal Government 2022). The introduction of any nutrient and/or greenhouse gas emissions tools should therefore be compatible with this nutrient register. The integration should be fast-tracked, and should include existing regulations, identification systems, and *Länder*-specific regulations and tools to the greatest extent. It should generate practical and efficient options for all stakeholders in its implementation, especially farmers (e.g., due to farm-specific suggestions for improvement to the N management) and control authorities (e.g., due to artificial intelligence-supported selection of farm visits). Besides control of regulatory thresholds, monetarization of N surpluses (e.g., levy, reward) would become possible with such a mandatory register. In this context, the COM provides the Farm Sustainability Tool (FaST) to EU-MS. This digital, app-based tool supports farmers in creating a fertilization plan with consideration of farm- and site-specific agronomic, soil, and climate conditions, while not being expected to be connected with penalties. The app was co-developed by several COM general directorates (DG Defence Industry and Space, DG Agriculture and Rural Development, DG Informatics) and *PwC* France, a private auditing and consultancy firm. Several EU-MS and regions have already tested the FaST nutrient management system, which will be available EU-wide from 2024 at the latest (European Commission 2020, 2023). There are currently discussions on including the tool in the plans for the next CAP in 2028, and on introducing a harmonized approach to budgeting for greenhouse gas and N emissions, thus involving a wide range of other EU-MS. In order to generate high acceptance and adoption among farmers, drivers and barriers need to be considered when developing and promoting digital tools for sustainable nutrient management (European Commission & EIP-AGRI 2022).

In addition to technological innovations and management improvements, indicators are needed to accurately measure environmental pollution, and to assess the effectiveness of measures over time. Robust and meaningful indicators with target-oriented threshold levels should be embedded in an efficient data collection and monitoring mechanism in regulations. Further evaluations are required to determine whether the current set of indicators is sufficient or not.

6.3 Limitations

Limitations of the methods used in this thesis are discussed in this section. The focus is mainly on FADN data, particularly the representativeness and inclusiveness of those data, and extraction of quantitative N flows from the data. First, it is worth mentioning that the FADN includes a large sample size (n = approximately 10,000, with minor annual divergency), including farms of different structure, from different *Länder*, and in different soil-climate areas. A total of around 20,000 variables are surveyed annually, covering financial accounting but also including information on physical amounts, e.g., of mineral fertilizers, yield, or livestock, which provides a comprehensive picture of farm nutrient budgeting.

In terms of representativeness, the BMEL, which is responsible for data collection, data validation and quality, and data provision, claims good representativeness of the agricultural sector (BMEL 2022c). Within the evaluation process on StoffBilV 2017, a sub-analysis compared samples based on German FADN data (used both in the evaluation process and in this thesis), and data from the latest national farm survey in 2016 (Löw et al. 2021). The results showed that UAA (-6% for FADN sample compared with national farm survey sample), cattle population (-1%), and pig population (<1%) displayed a high level of consistency, whereas poultry population (-79%) and other animal population (-81%) displayed a high level of divergence. A possible explanation is that farms without UAA (e.g., industrial livestock farms, biogas plants) and very small farms (<50,000 € standard output per annum) are not covered in the FADN data. There are also methodological differences in the calculations, with different reference periods (2016 for the national farm survey compared with three-year means between 2016/17 and 2018/19 for FADN) and different calculations of average animal numbers (e.g., definition of cutoff dates) that may contribute to the divergence observed. Errors due to sampling are quantified in the national farm survey, ranked between less than 2% to more than 15% (marked with the letters A (low) to E (high)). Additionally, the national farm survey offers a structural overview of agricultural characteristics, while specialist statistics provide specific and more detailed information on these characteristics (DESTATIS 2018).

Regarding inclusiveness, the FADN lacks some important information to accurately represent the nutrient budget of agricultural farms. A major weakness is lack of information on organic fertilizer amounts, although there are financial accounts on on-farm manure and on organic fertilizers in general. Besides the lack of data on N amounts, a more detailed breakdown into organic fertilizer types (e.g., excreta according to animal type, compost, digestate, and solid or liquid phase) would be beneficial, as physical properties and nutrient composition vary greatly (Wendland et al. 2018; Myrbeck et al. 2019). Detailed information on manure application technique and application date would also be relevant for analyzing farm nutrient management appropriately. These ideas for improvement were discussed, formulated, and submitted to the European administration in a COM survey by my research group as a targeted stakeholder group (European Commission 2022c). The COM is considering extensive additions to data acquisition on biodiversity and sustainability in the FADN with the implementation of the so-called Farm Sustainability Data Network (FSDN) (Barreiro Hurle et al. 2021; European Commission 2021), and issued a request to the federal ministries in Germany and downstream federal institutions, which includes Thünen Institute, in 2021.

In the statistical calculation program developed in this thesis, the quantities of organic fertilizers to be exported were derived by assuming compliance with the regulatory requirements, in particular the maximum application rate of 170 kg N from organic fertilizers per hectare UAA and year in § 6 DüV (2020). Amounts in excess of this limit, which must be sold, are of the order of magnitude of about 5 kg N/ha related to the UAA in Germany. However, the spatial distribution of exported manure and information on importing farms are not available from FADN data.

Normative derivation of traded manure amounts based on corresponding financial records and farm structure was avoided, since this approach is associated with too many uncertainties. Many factors may play a role, e.g., access to infrastructure, different regional pricing structure for manure, availability of application technology and know-how, availability of manure, etc.

In addition, default values for estimating N flows on-farm were used (e.g., for estimating crop-type specific BNF, crop-type specific nutrient content or potential gaseous N losses), as this is common and legal practice e.g., for documentation and reporting, due to practical reasons. Another shortcoming was estimation of physical amounts of imported feedstuff based on monetary data, through which accuracy was compromised. Frequent professional measurements are necessary for optimization of farm-specific N management, but are associated with high sampling, time, and monetary costs. Some of these limitations are also explained in previous studies using farm accounting data (Gamer & Bahrs 2010; Bach 2013; Bahrs & Gamer 2015; Ehrmann 2017; Barreiro Hurle et al. 2021), which were used in part as a theoretical basis for the method applied in this thesis. By attempting to use the most specific and differentiated factors possible while staying within the regulatory framework, the methodological work in this thesis sought to expand knowledge of data accuracy and to demonstrate new application possibilities (e.g., estimation of farm-level fertilization planning).

For the analysis in Paper II, three-year mean values were used as dependent and independent variables for farms with permanent representation in FADN, in order to achieve more stable indicator values. This made it difficult to analyze effects of e.g., new regulations, changes in production costs, or extreme weather events on indicator values and observed interrelations. For this purpose, analysis over a set period would be of interest. The statistical calculation program and econometric approach developed here offer the possibility to do so. As an example, changes in two independent variables, mineral fertilizers and operating profit from 2016/17 to 2021/22, are shown in Table A1.

Another limitation is that some bias may have been introduced because the farmers were aware of the assessment and verification of their data when participating in the FADN. This may have resulted in them being more accurate in reporting accounting processes and monetary flows more accurately, e.g., to avoid any hint of tax evasion. In qualitative research theory, this phenomenon is called “social desirability”, i.e., the tendency to respond according to social norms and expectations (Döring 2016). Analysis of N management is not a defined purpose of FADN data collection and many parameters are surveyed, so a possible bias is not ruled out, but can be disregarded to some extent.

With regard to the quantitative analysis of validated N indicators of dairy farms with different grazing intensities in Northwestern Germany in Paper III, the sample size (n = 30) was a limitation. The level of precision in the farm data was similar to that in other studies (Kelm et al. 2007; Gourley et al. 2012; Machmüller & Sundrum 2019). For comparison of the different grazing systems, however, this sample size was rather small. In particular, the sample size of the four management groups differed, and was particularly small for indoor housing (n = 5). Although the level of participation was relatively high (with 63 of 80 potential farms willing to join the study), data on only 30 farms were finally utilized, due to (1) extensive participation requirements, especially with regard to the software-based routine herd data recording, and (2) insufficient data management activities within the project, so that only around 50% of the participating farms could be considered. It is likely that growing acceptance and use of software-supported tools in agricultural and scientific data documentation and processing will increase the survey sample size, and thus statistical power, and improve data quality in future. In order to consider regional and farm structural differences, future studies should extend the analysis to different regions of Germany, to Europe, and to different continents.

7 Conclusions

A clear understanding of regulatory approaches and respective agri-environmental N indicators among policymakers is critical for establishment of controllable and feasible benchmarks and threshold values for N utilization, in order to make a timely contribution to achieving urgent national and international climate, environment, and sustainability goals.

A comparison of regulatory approaches in Germany and an assessment of the required parameters showed that gross farm-gate N balance is an agri-environmental N indicator with high data reliability and certainty, followed by soil surface N balance and fertilization planning. A high degree of data reliability and certainty can be achieved by using invoices, delivery notes, and product declarations for nutrients, and not including internal N flows such as manure or fodder produced and used on-farm. These aspects are characteristic of farm-gate balancing, making it easy for users and monitoring bodies to apply, in particular with software-supported tools. Practical and regulatory options for improvements identified in this thesis can make the regulatory approaches more robust and accurate, e.g., through use of standardized documentation on N contents in traded commodities or improved methodology for estimating BNF. Thus, this thesis made essential contributions to identification of robust N indicators, which are crucial for e.g., accurate reporting to authorities (e.g., COM), on-farm and official monitoring, acceptance of potential sanctions, transparency of legal requirements, and justiciability of measurements in the case of lawsuits. The findings in this thesis also improved understanding of the design, purpose, and data requirements of N indicators embedded in German legislation. A plurality of indicators and calculation methodologies are used in the agri-environmental context of N pollution, so the indicator value *per se* is not decisive.

The current levels of different N indicators were determined for the agricultural sector and several farm types in Germany, as were N reduction requirements based on legally defined framework and thresholds. The results revealed that the generalized threshold for gross farm-gate N balances (175 kg N/ha as a three-year mean) is not ambitious and was not restrictive for most farms studied, whereas complying with the farm-individual maximum N surplus was more challenging, especially for livestock farms. Based on this, a new methodological basis for calculating different agri-environmental N indicators on farm level based on farm accounting data was developed. It uses e.g., mineral fertilizer amounts, livestock numbers, excreta coefficients, imported feedstuff costs, and crop yields to quantify relevant N flows. This approach can be used to assess the impact of a wide range of policy measures *ex ante*, or to evaluate them *ex post*. With only minor modifications, such as adjustment of parameters and their coefficients, it can also be used for other externalities of agricultural activities beyond excessive N use, e.g., P or greenhouse gas emissions. Extension of system boundaries is possible, including processes in all stages of life cycle analysis. With respect to the intended change from FADN to FSDN as part of the COM *Green Deal*, the database and the statistical calculation program developed in this thesis will become even more robust over time. The program can be used by multiple stakeholders, e.g., farmers, consultants, policymakers, and control authorities, to serve different purposes such as measuring N performance on different spatial and system scales, optimization of on-farm N flows, defining indicative target values to be embedded in national legislation, monitoring and evaluation of policy measures, or controlling legally defined limits.

Using this statistical calculation approach, this thesis revealed high variance in NUE as an additional N performance indicator for different farm types. Livestock farms exceeded the target N surplus for the national N balance to such an extent that the sectoral sustainability goal defined in the German Sustainable Development Strategy and Climate Action Program 2030 could be jeopardized. The analysis also offered deep insights into regional, farm structural, and socio-economic patterns contributing to better N management. Efficiency was shown to be driven by characteristics such as crop selection and diversity, and intensity of manure application, although altitude, use of advisory services, and payments for agri-environmental-climate measures also played a significant role. Therefore, farm structure should be considered in agri-environmental policies e.g., through incentive management, such as funding policies (positive incentive, e.g., subsidies) or restrictions (negative incentive, e.g., sanctions), but the significance of selected regional and socio-economic characteristics should not be overlooked. This can lead to development of targeted optimization strategies to reduce N losses and act as guidance for policymakers formulating tailored measures in N policy, while particularly addressing drivers for reducing N surpluses and increasing NUE on different farm types.

In a sustainable intensification vision of agriculture, characterized by increasing yields and avoiding negative externalities and additional land use, NUE is often cited as an important indicator for assessing and monitoring N performance. NUE provides comprehensive information on on-farm N management and is not related to UAA but rather is non-dimensional. It is thus appropriate for identifying efficiency reserves on different spatial and system scales.

Dairy farms were found to have the lowest NUE of all farm types studied. Analysis of N indicators on different system levels for dairy farms with different grazing intensities, based on comprehensive farm data and findings of substance flow analysis, revealed efficiency reserves on feed, field, and farm level within each grazing system. Zero-grazing systems tended to show the best N performance, which may be attributable to more precise fertilization and feed management. This interplay of N balance and NUE should be considered when defining options for improving N management. Other criteria, such as animal welfare and biodiversity, are also relevant for holistic assessment of farming systems. A general problem identified in this thesis was overestimation of declared forage yields, leading to lower soil surface N surpluses. This may be because farmers report feed quantities used on-farm as an approximation, rather than as a precise measurement.

Overall, the methodology developed can serve as blueprint to help farmers check their data robustness. It can also be used to identify inefficient sub-systems and potential N loss zones in complex agricultural systems, while control authorities may benefit from the use of effective plausibility checks. In future versions based on standardized, automatic and software-supported data collection, the costs of documentation, monitoring, and assessment could be considerably reduced. The political will already exists in Germany, while experiences from other EU-MS (Denmark, the Netherlands) provide orientation. Amendments to relevant regulations, particularly the new assessment system for N and P farm-gate balances within StoffBilV, will require sustainable and resource-efficient N utilization. This offers an important opportunity to achieve environmental quality goals in the near future. The interplay of N balancing and NUE, together with defining benchmark values and a stringent assessment system, would mark a new era in German N policy and associated legislation. It is the responsibility of the research community to evaluate and critically assess proposed political measures in a timely way. Further investigations should focus on refining the NUE approach, as methodological harmonization and differentiated benchmarking are still lacking. Future studies should also analyze annual NUE in relation to climate scenarios and extreme weather events, with reference to rising greenhouse gas emissions and the impacts of ongoing climate change in the anthropogenic era.

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Appendix

Supplementary material to Papers I-III is included in the respective paper (see appendix).

Unpublished supplementary material to the thesis is provided in this section.

Table A1. Development and change of mineral fertilizer amounts and operating profits from 2016/17 to 2021/22 for all farms in German FADN, grouped according to region, farm type, livestock density, and federal state.

Regions[1]

	All farms			**Northwest**			**Central**			**South**			**East**		
	Sample	**N Input**[2]	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	10169	100	505	3435	103	741	1742	87	639	3351	82	787	1641	112	101
2017/18	9953	93	595	3323	90	809	1691	80	698	3322	78	939	1617	109	178
2018/19	9849	86	459	3318	88	609	1700	74	713	3239	73	771	1592	97	73
2019/20	9652	86	539	3275	87	847	1715	73	716	3038	74	756	1624	97	118
2020/21	8845	84	458	2920	84	557	1581	73	685	2754	70	708	1590	97	147
2021/22	8074	74	672	2611	71	1005	1459	63	800	2547	62	891	1457	87	237
Δ 3 yr. mean[3] [%]		***-12.5%***	***+7.0%***	Δ	***-13.9%***	***+11.5%***	Δ	***-13.5%***	***+7.4%***	Δ	***-11.2%***	***-5.7%***	Δ	***-11.8%***	***+42.6%***

Farm types

	Arable farming			**Vegetable farms**			**Permanent crop farms**			**Dairy farms**			**Other cattle & grazing farms**		
	Sample	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	2409	121	324	310	103	9046	702	52	3289	2958	86	587	1028	56	299
2017/18	2489	117	318	266	80	8419	672	49	3908	2835	80	975	1010	50	433
2018/19	2557	107	323	263	60	10249	635	42	3353	2795	77	660	1034	50	282
2019/20	2549	109	344	179	64	13796	623	45	3561	2795	77	566	1058	49	286
2020/21	2379	104	347	155	53	11098	588	46	3957	2570	74	577	1001	48	293
2021/22	2185	97	482	106	88	12895	532	39	3813	2379	59	961	913	31	468
Δ 3 yr. mean [%]		***-10.0%***	***+21.6%***	Δ	***-15.7%***	***+36.4%***	Δ	***-8.4%***	***+7.4%***	Δ	***-13.8%***	***-5.3%***	Δ	***-18.6%***	***+3.3%***

Farm types

	Pig and poultry farms			**Mixed farms**		
	Sample	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	912	98	1167	1849	106	313
2017/18	877	82	835	1804	97	328
2018/19	833	70	547	1731	90	234
2019/20	795	68	1520	1652	89	329
2020/21	797	70	414	1354	88	269
2021/22	675	67	629	1284	78	448
Δ 3 yr. mean [%]		***-18.0%***	***+0.5%***	Δ	***-13.5%***	***+19.7%***

Livestock density

	0 LSU/ha			**Up to 0.5 LSU/ha**			**Up to 1 LSU/ha**			**Up to 1.5 LSU/ha**			**Up to 2 LSU/ha**		
	Sample	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	2826	119	650	1493	104	165	1579	89	275	1476	83	576	1208	88	799
2017/18	2831	115	617	1499	97	224	1527	80	399	1401	78	737	1186	82	998
2018/19	2869	106	638	1486	87	146	1503	74	283	1406	73	525	1159	79	688
2019/20	2808	107	650	1509	87	186	1481	72	318	1380	75	641	1145	80	873
2020/21	2643	103	628	1440	82	226	1381	73	306	1237	72	487	1083	74	600
2021/22	2361	97	764	1375	75	337	1294	60	429	1130	63	725	981	57	1073
Δ 3 yr. mean [%]		***-9.6%***	***+7.3%***	Δ	***-15.4%***	***+39.8%***	Δ	***-15.7%***	***+9.9%***	Δ	***-9.9%***	***+0.8%***	Δ	***-15.5%***	***+2.5%***

Livestock density

	Up to 2.5 LSU/ha			**Up to 3 LSU/ha**			**More than 3 LSU/ha**		
	Sample	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	811	96	935	379	100	1124	397	102	1621
2017/18	778	85	1250	356	86	1332	375	82	1675
2018/19	753	82	854	342	83	843	331	77	1150
2019/20	694	81	978	316	77	1297	319	74	2114
2020/21	551	84	753	252	72	581	258	75	850
2021/22	499	61	1409	223	70	1446	211	61	1664
Δ 3 yr. mean [%]		***-14.5%***	***+3.3%***	Δ	***-18.2%***	***+0.8%***	Δ	***-19.5%***	***+4.1%***

Federal states

	Schleswig-Holstein			**Lower Saxony**			**North Rhine-Westphalia**			**Hesse**			**Rhineland-Palatinate**		
	Sample	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	653	124	461	1477	100	742	1283	96	906	634	84	426	972	91	915
2017/18	617	107	604	1458	86	824	1236	85	879	625	79	471	929	82	980
2018/19	651	114	336	1413	82	631	1240	81	726	642	74	410	933	74	1084
2019/20	659	112	498	1340	83	830	1265	79	1023	646	73	500	944	74	994
2020/21	544	109	455	1253	78	540	1110	77	643	564	73	446	901	73	997
2021/22	471	87	783	1096	65	1015	1033	70	1114	511	64	514	837	64	1166
Δ 3 yr. mean [%]		***-10.9%***	***+23.9%***	Δ	***-15.6%***	***+8.6%***	Δ	***-13.7%***	***+10.7%***	Δ	***-10.8%***	***+11.8%***	Δ	***-14.9%***	***+6.0%***

Federal states	**Baden-Württemberg**			**Bavaria**			**Saarland**			**Brandenburg**			**Mecklenburg-West Pomerania**		
	Sample	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	1213	88	751	2138	80	802	136	91	174	308	84	61	272	143	-24
2017/18	1173	78	825	2149	78	987	137	76	340	299	81	128	243	141	162
2018/19	1082	75	740	2157	72	784	125	77	344	311	79	112	217	118	65
2019/20	919	81	731	2119	72	766	125	66	336	306	75	115	230	128	165
2020/21	722	71	608	2032	70	750	116	64	345	301	70	142	196	124	171
2021/22	686	59	720	1861	64	963	111	45	397	289	62	238	171	118	221
Δ 3 yr. mean [%]		***-12.8%***	***-11.1%***	Δ	***-10.4%***	***-3.6%***	Δ	***-28.1%***	***25.6%***	Δ	***-15.2%***	***64.7%***	Δ	***-7.8%***	***173.4%***

Federal states	**Saxony**			**Saxony-Anhalt**			**Thuringia**		
	Sample	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**	**Sample**	**N Input**	**Profit**
Year	N	kg N/ha	€/ha	N	kg N/ha	€/ha	N	kg N/ha	€/ha
2016/17	388	101	141	375	106	217	296	126	160
2017/18	392	104	228	385	102	197	296	115	199
2018/19	401	94	92	385	86	52	277	110	35
2019/20	405	96	124	385	83	85	297	103	85
2020/21	390	98	173	382	85	125	320	103	115
2021/22	341	83	207	339	70	303	316	98	203
Δ 3 yr. mean [%]		***-7.6%***	***9.3%***	Δ	***-19.1%***	***10.0%***	Δ	***-13.5%***	***2.5%***

[1] *Northwest = SH, HH, NI, HB, NW; Central = HE, RP, SL; South = BW, BY; East = MV, BB, BE, ST, SN, TH.*

[2] *Mean amounts of mineral fertilizers applied in the respective year.*

[3] *Difference between three-years mean of 2016/17 to 2018/19 and 2019/20 to 2021/22.*

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Inspired by Hermann Hesse “Stufen” (1943, Switzerland): A magic dwells in each *ending*.

Declarations

1. I, hereby, declare that this dissertation has no not been presented to any other examining body either in its present or a similar form. Furthermore, I also affirm that I have not applied for a Ph.D. at any other higher school of education.

Göttingen, 27.04.2023

(Signature)

PHILIPP LÖW

(Name in block capitals)

2. I, hereby, solemnly declare that this dissertation was undertaken independently and without any unauthorized aid.

Göttingen, 27.04.2023

(Signature)

PHILIPP LÖW

(Name in block capitals)

3. I hereby declare that the digital version of this dissertation matches the printed version of this dissertation.

Göttingen, 27.04.2023

(Signature)

PHILIPP LÖW

(Name in block capitals)

Table A2. Authorship contribution statement.

Paper and contribution		**Authors**			
		PL	**BO**	**SK**	**YNK**
I	Conceptualization	X	X	X	
	Methodology	X	X		
	Visualization	X	X		
	Software	X	X		
	Writing (review and editing)	X	X	X	
II	Conceptualization	X	X		
	Methodology	X	X		
	Visualization	X			
	Software	X			
	Writing (review and editing)	X	X		
III	Conceptualization	X	X		X
	Methodology	X			X
	Visualization	X			X
	Software	X	X		X
	Writing (review and editing)	X	X		X

"X" indicating the author´s contribution; PL = Philipp Löw, BO = Bernhard Osterburg, SK = Susanne Klages, YNK = Yusuf Nadi Karatay