Agricultural Systems 213 (2024) 103796

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

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

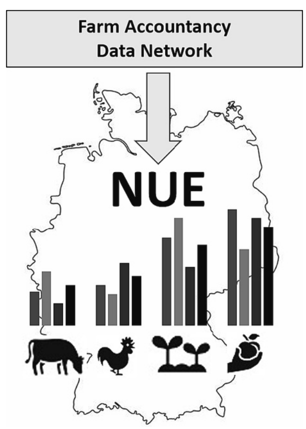
Philipp Löw[a,b,*], Bernhard Osterburg[a]

[a] Coordination Unit Climate and Soil, Thünen Institute, 38116 Braunschweig, Germany
[b] Plant Nutrition and Crop Physiology, Department of Crop Science, University of Göttingen, 37075 Göttingen, Germany

HIGHLIGHTS

- We calculated Nitrogen (N) use efficiencies and N balances for different farm types using German Farm Accountancy Data Network.
- We found high variance in N performance within farm types for 2017 to 2019, indicating efficiency reserves in N utilisation.
- Based on calculated N indicators, farms with animals would miss national Sustainable Development Goals for 2030.
- Nitrogen indicators were interrelated with regional, farm structural and socio-economic factors.

GRAPHICAL ABSTRACT



ARTICLE INFO

Guest Editor: Dr. Pytrik Reidsma

Keywords:
Nitrogen use efficiency
Nitrogen balance
Agri-environmental indicator
Sustainable intensification
Nutrient policy

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 evaluate N performance of the German agricultural sector, to generate knowledge gain regarding methodological design and estimating N indicators based on farm accounting data, to estimate the role and extent of externalities, 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) covering 5923 farms between the years 2016/17 and 2018/19, we calculated mean farm-level NUE and N balance values for six farm types,

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.

* Corresponding author at: Coordination Unit Climate and Soil, Thünen Institute, 38116 Braunschweig, Germany.
E-mail address: philipp.loew@thuenen.de (P. Löw).

https://doi.org/10.1016/j.agsy.2023.103796
Received 12 January 2023; Received in revised form 17 October 2023; Accepted 23 October 2023
Available online 29 October 2023

considering input and output parameters on farm level as well as externalities. 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. Different levels of externalisation, namely feed imports and manure exports, may deepen this gap. 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 and Lassaletta, 2022), environmental protection (Schulte-Uebbing et al., 2022), preservation of biodiversity (Dise et al., 2011), protection of human health (Sutton and 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 and Garnett, 2014), conservation agriculture, agroforestry, integrated pest management (Godfray and Garnett, 2014) and improved N utilisation (EUNEP, 2015; Oenema, 2015), in order to “sustainalise[1]” agriculture.

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). Nitrogen use efficiency 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) (eq. 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. Nitrogen 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 (eq. 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).

[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).

$$Farm - gate\ N\ balance\ (FarmB)\ [kg\ N/ha] = \frac{Imported\ N\ [kg\ N] - Exported\ N\ [kg\ N]}{Utilised\ agricultural\ area\ [ha]} \quad (1)$$

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

where:

$$Exported\ N\ [kg\ N] = \sum Yield\ of\ marketed\ crops, livestock, animal\ products, organic\ fertiliser, seeds\ and\ plant\ material$$

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

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 and 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):

1.4.1. 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).

1.4.2. 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).

1.4.3. Socio-economic level

- H7: With increasing farm manager age, N performance improves due to experience (Osterburg, 2007; Jan et al., 2017).

Table 1
Parameters considered for estimating Nitrogen balance and Nitrogen 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).
Atmospheric N deposition	Non-agricultural atmospheric N deposition specified on federal state level, based on Bach et al. (2020), German Environment Agency (2023) and Geupel et al. (2021).
Outputs / exports	
Yield	Crop-specific revenues and prices according to FADN, crop-specific N-coefficients according to Gamer and 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 production is based on animal category- and management-specific N-excretion rates per head (FADN) according to § 6 DüV (2020). For exports, on-farm manure amounts of >170 kg N/ha are compulsorily exported according to DüV (2020).
Seeds, crop material	Inferred from the quantities sold.

- H8: With increasing education level of the farm manager, N performance improves due to better knowledge (Nieberg and von Münchhausen, 1996; Osterburg, 2007; Prokopy et al., 2008).
- H9: With increasing operating profit, N performance improves due to better farm management (Nieberg and von 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. Externalities for exported manure were considered using an adjusting factor of 0.4, derived as respective manure N efficiency from farm data, following Quemada et al. (2020) or Löw et al. (2020). Hence, exported manure is not considered as a fully marketable final product. The adjusting factor for exported manure provides that N losses occurring outside the investigated farm are considered for calculating farm-NUE as if the manure would be used for plant production in an average farm. For harmonisation, this is also applied to FarmB calculation. 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.

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.

Although ATD is not included in official assessment of farm-gate N balance (StoffBilV, 2017), it was considered as a relevant input parameter for higher transparency and better comparability. Non-agricultural ATD was deduced on a federal state level, ranging from 3.9 kg N/ha/yr (Rhineland-Palatinate) to 7.2 kg N/ha/yr (North Rhine-Westphalia), as agricultural gaseous emissions are already implied due to the gross calculation approach. 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

2.2.1. 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 and Offermann, 2020), we used both location parameters to improve understanding of the data.

2.2.2. Multiple regression analysis

In addition, we performed multiple regression analysis with continuous and dummy variables for non-interval categorised variables (Urban and 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 (eq. 3) where further determinants of FarmB and farm-NUE were added, grouped into regional, farm structural and socio-economic variables:

$$y = a_0 + a_1 \times x_1 + a_2 \times x_2 + \ldots + a_n \times x_n \tag{3}$$

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).

2.3. 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 >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

Farm-gate N balances 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 63 kg N/ha for FarmB and 60% for farm-NUE. Permanent crop and arable farms showed the lowest FarmB and highest farm-NUE, while for farm types with animals, FarmB decreased from pig and poultry farms (156 kg N/ha) to dairy farms (102 kg N/ha), mixed production systems (67 kg N/ha), and other cattle and grazing livestock farms (56 kg N/ha). For farm-NUE, the order of increase was dairy farms (40%), pig and poultry farms (49%), other cattle and grazing livestock farms (50%), and mixed production systems (60%) (Table 2). An additional analysis only for animal farms revealed farm-NUE of 48% (0.4 StdMean) and FarmB of 93 kg N/ha (1.3 StdMean), while for farms without animals farm-NUE was 100% (1.7 StdMean) and FarmB was 14 kg N/ha (1.0 StdMean). Organic farming showed slightly higher farm-NUE (62%) and lower FarmB (26 kg N/ha) than conventional farming (60% and 67 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.

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.

FarmB and farm-NUE for farm types with animals are shown as boxplots (10th to 90th percentile) in Fig. 1. For FarmB, pig and poultry farms (154 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 (60%) and lowest for dairy farms (41%). 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.

As shown in Fig. 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 Fig. 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 2.5%. The total sample of 3989 farms with animals was reduced to 3893, due to missing values or lack of compatibility with defined axes. The majority of animal farms retained were densely distributed between a

Table 2
Overview of the sectoral, farm type-specific, production type-specific, region-specific and manure production-specific Nitrogen balance and Nitrogen use efficiency values on farm level between 2016/17 and 2018/19 ($n = 5923$).

Scale type	Sample size (n)	Indicator					
		N balance (kg N/ha)			N use efficiency (%)		
		Trimmed mean	StdMean	Median	Trimmed mean	StdMean	Median
All	5923	63	1.065	49	60	0.520	60
Farm type							
Arable	1522	18	1.255	13	94	1.324	96
Dairy	1744	102	1.739	91	40	0.373	41
Other cattle	573	56	3.307	32	50	1.498	55
Pig, poultry	543	156	3.143	153	49	0.706	51
Permanent	410	5	1.314	8	145	9.868	115
Mixed	1129	67	1.833	58	60	0.800	60
Production type							
Organic	506	26	2.036	20	62	2.945	59
Conventional	5415	67	1.129	56	60	0.522	60
Region							
South	2087	48	1.650	37	67	1	63
East	896	54	2.228	49	58	1	54
West	1561	80	2.376	59	57	1	60
North	1377	76	2.195	72	58	1	57
Organic fertiliser production[1]							
0–40 kg Norg/ha	2286	17	0.925	13	96	1.547	93
40–120 kg Norg/ha	1622	63	1.319	50	53	0.675	56
>120 kg Norg/ha	2013	136	1.636	126	43	0.354	43

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

Table 3
Overview of the sectoral and farm type-specific accumulated mean Nitrogen input and output parameters considered for calculating investigated Nitrogen indicators on farm level (n = 5923).

Scale type	Sample size (n)	N inputs (kg N/ha)				N outputs (kg N/ha)			
		Mean	Median	Q1	Q3	Mean	Median	Q1	Q3
All	5923	156	137	73	203	97	82	43	122
Farm type									
Arable	1522	126	128	82	165	120	119	91	144
Dairy	1744	169	154	91	223	71	60	40	86
Other cattle	573	108	92	29	164	64	41	14	88
Pig, poultry	543	346	309	239	398	181	160	106	223
Permanent	410	46	36	15	56	31	25	23	27
Mixed	1129	164	147	88	203	120	89	60	119

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

maximum of around 190 kg N/ha for FarmB and 100% for farm-NUE, indicating the 80% confidence interval. For pig and poultry farms ($R^2 = 0.36$) and dairy farms ($R^2 = 0.32$), the distribution cloud was more right-leaning, while for mixed production systems ($R^2 = 0.44$) and other cattle and grazing livestock farms ($R^2 = 0.26$) 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 (Fig. 2).

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 ($R^2 = 0.42$), while the value was $R^2 = 0.45$ for the advanced multiple regression model. Goodness of fit was considerably lower for the models explaining farm-NUE ($R^2 = 0.21$ and 0.23 in baseline and advanced regression, respectively). This pattern was also observed for the subsamples, with the highest goodness of fit observed for the West ($R^2 = 0.49$ for FarmB) and North ($R^2 = 0.34$ for farm-NUE) region. Goodness of fit was generally higher for subsamples with comparatively higher manure intensity. The regression results for different variables are described in detail below.

3.2.1. 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 (−0.4%, $p < 0.01$) and cattle manure (−0.3%, $p < 0.01$). The effect of an increase of 1 kg N/ha in organic manure on FarmB ranged from 0.5 to 1.8 kg N/ha in the different regions, while the effect on farm-NUE ranged from −0.1 to −0.5%. In an additional analysis, we grouped the farms according to cattle and pig

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

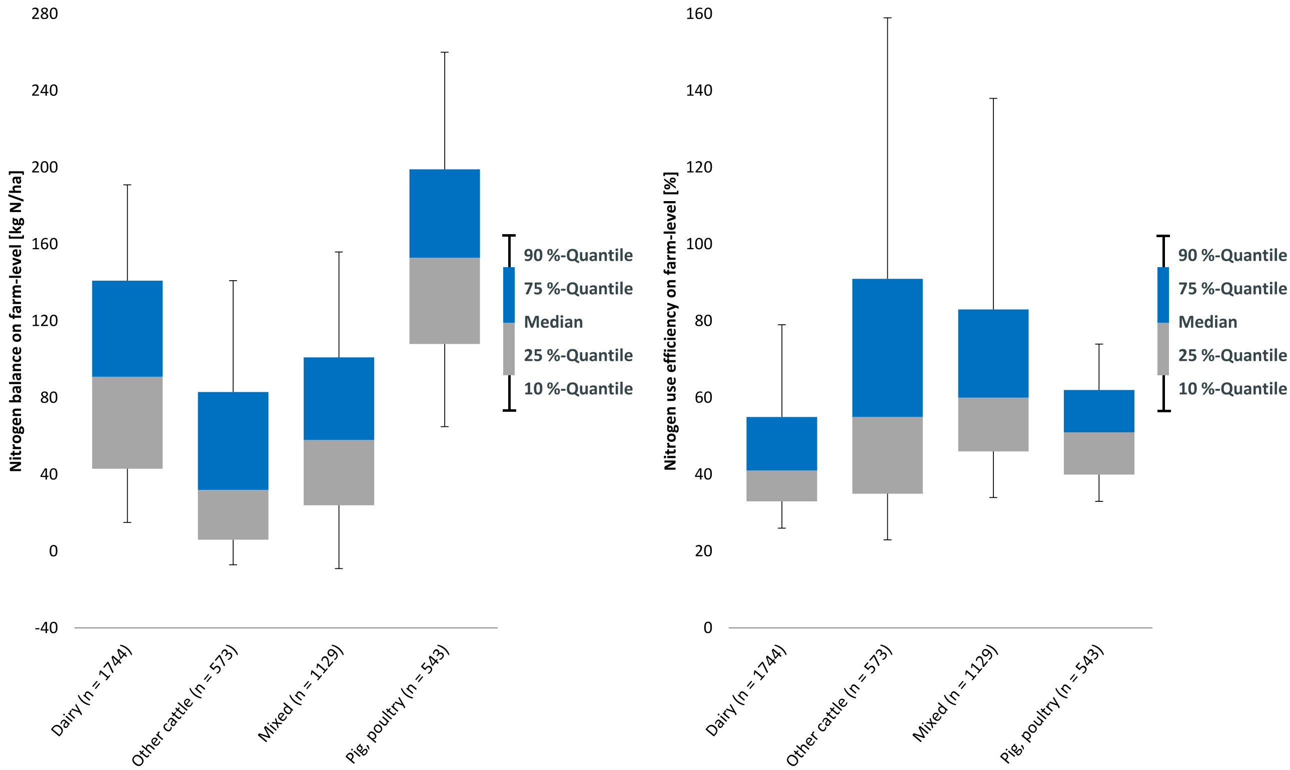


Fig. 1. Nitrogen balance values (left) and Nitrogen use efficiency values (right) on farm level as three-year means (2016/17–2018/19) for investigated farms with animals (n = 3989).

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, each unit increase in intensity of manure application having a significantly decreasing effect on farm-NUE while this effect was lowest for high-intensity application (−0.3% and − 0.2%). Overall, the coefficients varied only slightly. For pig manure, high manure application intensity had the greatest effect in both increasing FarmB (+0.8 kg N/ha) and decreasing farm-NUE (−0.2%).

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 (all −0.4 kg N/ha, $p < 0.01$) and maize (−0.3 kg N/ha, $p < 0.01$), while a positive effect was found for rapeseed yield whereby 1 additional kg N/ha yield increased FarmB by 0.3 kg N/ha ($p < 0.01$). Higher N yields had an increasing effect on farm-NUE for all crops and crop groups except potato yield in East 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 (+0.1%, $p < 0.01$). 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 (+24%, $p < 0.01$). For other crops, the results were significant for farm-NUE (13.6%, $p < 0.01$), so that a 10% increase in cultivated area was associated with a 1.4% increase in farm-NUE.

In terms of production type, organic farming showed a decreasing effect on FarmB (−25.4 kg N/ha) compared with conventional farming. A significant decreasing effect was also observed for the different regions, where it was highest in North (−36.8 kg N/ha) and lowest in East (−17.2 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 (+4.5%, $p < 0.01$) 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 >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 (increasing farm-NUE only in the West region), while spring grain showed an increasing effect only on farm-NUE (highest for East). Wheat, winter grain, maize, potato and grassland 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. Detailed results can be found in Tables 4 and 5.

3.2.2. Regional interrelations

The geographic region in which farms were located influenced FarmB and farm-NUE. Farms located in the South (+2.9%, $p < 0.01$) and East (+2.3%, $p = 0.02$) regions had significantly higher farm-NUE than farms in North. 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 (−12.0 kg N/ha), while for high organic input systems the effect was highest in South (−14.2 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, affected FarmB in low soil quality farms (+4.7 kg N/ha, $p = 0.02$). Altitude had significant results on FarmB and farm-NUE. Medium altitude had the strongest decreasing effect on farm-NUE (−8.0%, $p < 0.01$) 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.

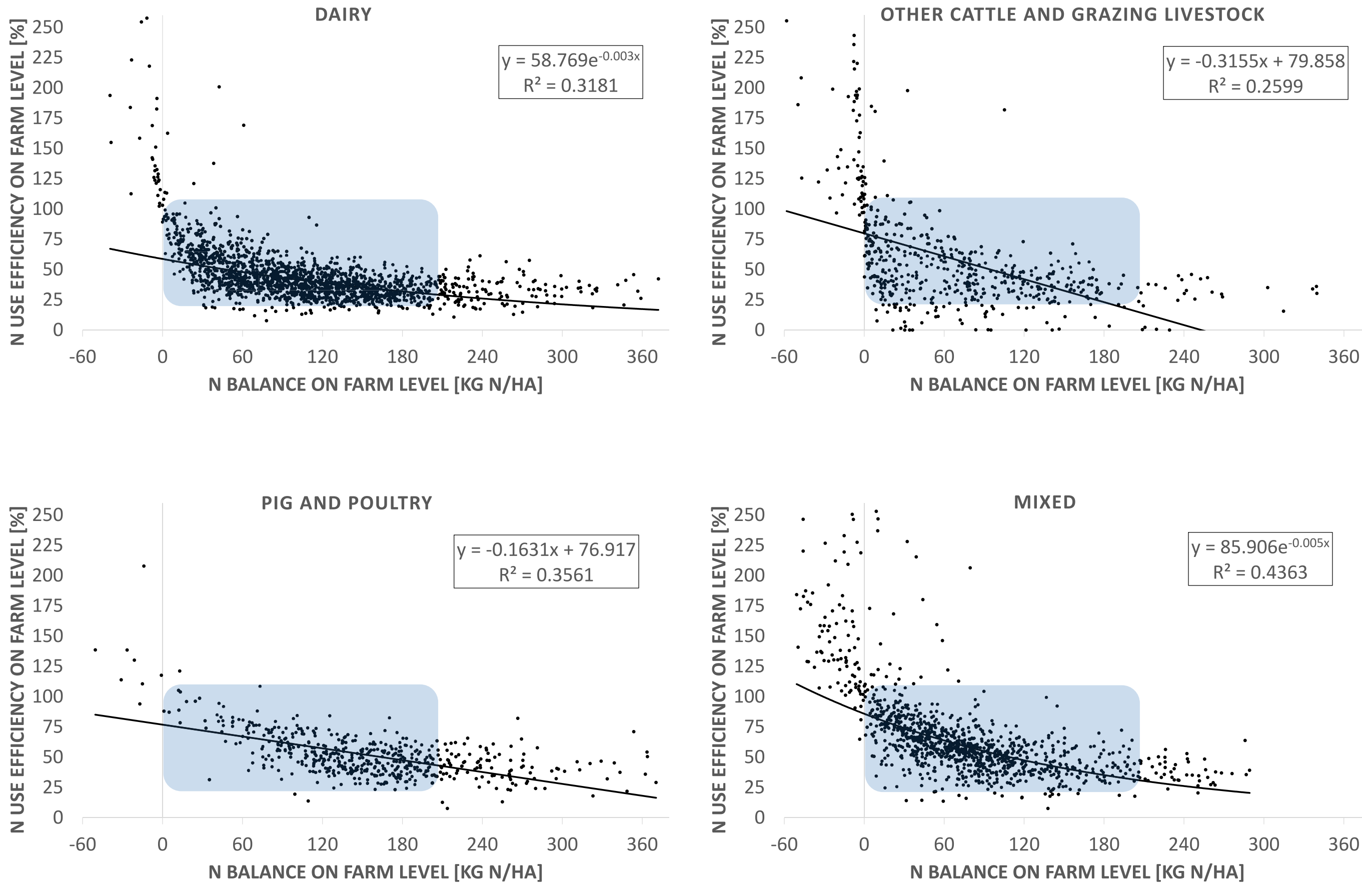


Fig. 2. Farm type-specific Nitrogen use efficiency on farm level (farm-NUE) in relation to Nitrogen balance on farm level (FarmB) and farm type as three-year means (2016/17–2018/19) for farms with animals in the trimmed dataset (n = 3893). (Shaded area = 80% confidence interval of farm-NUE and FarmB for investigated farms with animals.)

Similar results were found for high organic N input systems and farm types with animals. For increasing irrigated area, no significant results were observed.

3.2.3. *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 (+3.2%, p = 0.01) for small farms. The increasing effect on farm-NUE was also observed for high organic N input systems (+2.9%) and for farms with animals (+2.5%). Significant results were observed for farm manager's age, as younger age was linked to lower farm-NUE (−2.8%, p = 0.01) compared to older age group. Medium school education had the strongest effect on farm-NUE (+2.7%, p < 0.01). Similarly, medium agricultural education had a decreasing effect on FarmB (−5.2 kg N/ha, p = 0.02) compared with high agricultural education. 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 (−5.8%, p < 0.01). Low use of consulting services was interrelated with decreased farm-NUE (−2.5%, p < 0.01). An increase in payments received for AECM in €/ha caused both a significant decrease in FarmB (−0.02 kg N/ha) and an increase in farm-NUE (+0.01%). 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 and decreased farm-NUE.

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.

4. Discussion

4.1. *Main findings*

4.1.1. *Nitrogen balance and nitrogen 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 63 kg N/ha, farm-NUE 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:

Table 4
Overview of the sectoral and region-specific results of the baseline multiple regression model for Nitrogen balance (N balance) and Nitrogen use efficiency (NUE) on farm level ($n = 5923$).

Independent variables	Description	Unit	All farms: N balance (kg N/ha)	All farms: NUE (%)	South: N balance (kg N/ha)	South: NUE (%)	East: N balance (kg N/ha)	East: NUE (%)	West: N balance (kg N/ha)	West: NUE (%)	North: N balance (kg N/ha)	North: NUE (%)
			Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
Organic manure - cattle		kg N/ha	1.0*	−0.3*	1.1*	−0.4*	1.2*	−0.3*	1.0*	−0.3*	0.7*	−0.2*
Organic manure - pig		kg N/ha	0.8*	−0.2*	0.8*	−0.2*	0.8*	−0.2*	0.9*	−0.2*	0.8*	−0.1*
Organic manure - poultry		kg N/ha	1.1*	−0.2*	1.1*	−0.2*	1.8*	−0.1	1.0*	−0.2*	1.1*	−0.1*
Organic manure - other animals		kg N/ha	0.6*	−0.4*	0.8*	−0.5*	0.9*	−0.4*	0.6	−0.4*	−0.1	−0.2
Organic manure - digestate		kg N/ha	0.6*	−0.2*	0.8*	−0.4*	0.1	0.3	0.9*	−0.1	0.5*	0.0
Wheat yield		kg N/ha	−0.1	0.2*	−0.1	0.3*	−0.2	0.4*	0.1	0.2*	0.0	0.2*
Rye yield		kg N/ha	0.2	0.3*	0.7*	0.0	0.3	0.1	0.0	0.3	−0.2	0.2*
Winter grain yield		kg N/ha	0.0	0.1*	0.2	0.0	0.2	0.2*	−0.1	0.2*	0.0	0.2*
Spring grain yield		kg N/ha	0.0	0.2*	0.2	0.1	0.0	0.2*	−0.2	0.1	0.0	0.2*
Maize yield		kg N/ha	−0.3*	0.3*	−0.3*	0.4*	−0.2	0.2*	−0.3*	0.3*	−0.3*	0.2*
Rapeseed yield		kg N/ha	0.3*	0.3*	0.0	0.4*	0.5*	0.3*	0.5*	0.3*	0.3	0.2*
Sugar beet yield		kg N/ha	−0.4*	0.5*	−0.5*	0.6*	−1.8*	1.2*	−0.2	0.5*	−0.4*	0.5*
Potato yield		kg N/ha	0.1	0.3*	0.4	0.2	1.0	−0.1	0	0.3*	0.1	0.3*
Grassland yield		kg N/ha	−0.4*	0.2*	−0.6*	0.3*	−0.8*	0.3*	−0.1	0.1*	0.0	0.1*
Vegetable area (factor)		ha/ha	12.5	24.4*	24.3	−0.5	−108.1*	295.7*	24.8	26.4	−90.6*	27.6
Grain legumes yield		kg N/ha	0.2	0.0	0.1	0.0	0.9*	−0.3	−0.1	0.1	−0.2	0.3*
Other crops area (factor)		ha/ha	−8.3	13.6*	−2.2	10.8*	−20.0	37.3*	−2.1	−0.3	−12.7	17.5*
Production type	organic	0: no; 1: yes	−25.4*	4.5	−18.3*	4.5	−17.2*	−1.1	−28.1*	8.2*	−36.8*	1.2
	conventional	0: no; 1: yes										
Payments for AECM[1]		€/ha	−0.04*	0.02*	0.00	0.01	−0.05	0.01	−0.06*	0.03*	−0.07*	0.01
Observations		n	5923	5923	2087	2087	896	896	1561	1561	1376	1376
Goodness of fit		R^2	0.42	0.21	0.40	0.15	0.35	0.26	0.49	0.28	0.45	0.34

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).

(1) Our calculations were for relevant parameters according to StoffBilV (2017), the official regulation on recording and assessing farm-gate balances, with minor adjustments. 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 on grassland for other cattle and grazing livestock farms in a subanalysis. These additional N inputs decreased farm-NUE for other cattle farms by 2%, with NUE on sectoral level remaining rather 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 organic farms and 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 and Schulte-Uebbing, 2020).

(3) Farms with animals (dairy farms, other cattle and grazing livestock farms, pig and poultry farms) showed a farm-NUE of 48% 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 (Fig. 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 and Bleeker, 2013; De Vries and 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, externalisation effects for the end use of exported manure were considered, using an adjusting factor reflecting manure N efficiency (40%) of the sampled farms. Also in a recent study, Quemada et al. (2020) investigated the effect of externalised N inputs and outputs 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

Table 5
Overview of the sectoral, manure application-specific and farm type-specific results for selected regional and socio-economic variables of the advanced multiple regression model for Nitrogen balance (N balance) and Nitrogen use efficiency (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	NUE	N balance	NUE	N balance	NUE	N balance	NUE	N balance	NUE
			(kg N/ha)	(%)	(kg N/ha)	(%)	(kg N/ha)	(%)	(kg N/ha)	(%)	(kg N/ha)	(%)
			Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
Region												
Large geographic regions	South	0: no; 1: yes	−8.5*	2.9*	−6.7*	5.0	−14.2*	0.3	−6.8*	6.1	−12.0*	1.5
	East	0: no; 1: yes	−9.0*	2.3*	−12.0*	9.0*	−8.9*	−2.3*	−14.1*	10.5*	−8.6*	−0.5
	West	0: no; 1: yes	0.5	−0.4	−7.4*	6.3*	1.5	−2.2*	−7.1*	5.2	1.4	−1.5
	North	0: no; 1: yes										
Altitude	low	0: no; 1: yes	16.9*	−4.2*	1.4	−4.3	12.3*	−5.7*	3.7	2.5	12.6*	−4.8*
	medium	0: no; 1: yes	19.2*	−8.0*	3.8	−5.2	17.7*	−7.9*	3.1	2.7	17.3*	−7.6*
	high	0: no; 1: yes										
Socio-economic												
Farm size	low	0: no; 1: yes	−8.4*	3.2*	−7.9*	3.7	−4.7	2.9*	−11.5*	2.9	−2.5	2.5*
	medium	0: no; 1: yes	−3.2	0.6	−4.6	0.0	−0.7	−0.1	−8.5*	1.0	1.4	−0.3
	high	0: no; 1: yes										
Age	low	0: no; 1: yes	3.6	−2.8*	6.1	−8.4*	0.7	0.1	3.8	−6.2	2.4	−0.3
	medium	0: no; 1: yes	1.3	−1.3*	1.1	−3.1	1.0	−0.2	1.9	−2.2	0.6	−0.4
	high	0: no; 1: yes										
School education	low	0: no; 1: yes	−2.1	1.0	−2.3	3.1	−6.6	0.9	−0.8	3.6	−5.9	1.8
	medium	0: no; 1: yes	−5.2*	2.7*	−5.0*	4.1	−10.9*	1.5	−3.6	3.9	−9.5*	3.0*
	high	0: no; 1: yes										
Agricultural education	low	0: no; 1: yes	−1.1	0.7	−1.6	1.8	−1.6	−0.5	0.7	1.0	−2.4	−0.3
	medium	0: no; 1: yes	−3.9*	0.2	2.0	−2.3	−8.0*	0.6	2.1	−2.8	−7.9*	0.5
	high	0: no; 1: yes										
Operating profit	low	0: no; 1: yes	10.4*	−5.8*	4.3	0.9	15.9*	−6.9*	9.9*	−5.3	11.4*	−6.5*
	medium	0: no; 1: yes	4.4*	−3.2*	0.3	3.3	7.8*	−3.8*	4.3	−2.0	6.0*	−3.8*
	high	0: no; 1: yes										
Consulting services	low	0: no; 1: yes	9.2*	−2.5*	3.0	−3.6	13.6*	−1.0	0.1	−1.7	13.6*	−1.7*
	high	0: no; 1: yes										
Payments for AECM[1]		€/ha	−0.02*	0.01*	−0.01	0.01	−0.04*	0.00	−0.01	0.00	−0.04*	0.01
Number of employees		heads	0.13*	−0.09*	0.12*	−0.17*	0.45*	0.01	0.10	−0.16*	0.38*	0.01
Observations		n	5923	5923	2478	2478	3445	3445	1932	1932	3991	3991
Goodness of fit		R^2	0.45	0.23	0.19	0.09	0.37	0.22	0.18	0.06	0.41	0.18

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).

and country. In this study, we conducted a subanalysis considering externalities with different efficiency levels for purchased feed and sold manure (see Table A5). 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 50% while it is 42% for less efficient systems. However, there is no indication that farms with high feed imports or manure exports are inevitably related to good N indicator values in our study. Especially for pig and poultry farms as well as for dairy farms, the level of externalisation (mainly for purchased feed) plays a key role for the assessment of N performance, resulting in a variation up to ±5 percentage points in our analysis. Thus, our 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.

4.1.2. 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.

4.1.3. 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. Also, underestimation of manure import and BNF might be explicative. 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, not 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 and von 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 high N exports in harvested 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. The effect of vegetable area was variable and not coherent among regions. As specialised vegetable farms are not part of the analysis, these are often arable farms with minor vegetable farming, inherently showing high NUE values, and accounting for only 2% of all farms investigated. Also, the significant use of compost in vegetable farming as an additional N input might be underestimated here. Interestingly, farms with low crop diversity were associated with significantly better N performance, possibly owing to their highly specialised technical equipment and management activities.

4.1.4. Regional interrelations

An increase in natural yield potential did not have a significant effect on the N indicators investigated, neither for all farms nor 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 plain 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 and 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).

4.1.5. *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 high organic application intensity or farms with 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 and von Münchhausen, 1996; Buckley et al., 2016; Jan et al., 2017). For farmers age, significant results were found, where a decreasing effect on NUE was observed for the young and middle 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 N losses. 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 +1000 €/ha for AECM reducing FarmB by −24 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

Farm-gate balancing 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.

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. Thus, our results provide a theoretical and quantitative basis for federal authorities to develop farm (type)-specific recommendations with regard to farm-NUE.

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 farms with potential for improving efficiency and difficulties meeting current sustainability goals, as these are mainly farms rearing animals, especially ruminants. Thus, the consideration of different levels for externalisation on upstream (feed imports) and downstream (manure exports) products affect the N performance considerably. In our sample, there was no indication that farms with high feed imports or manure exports are inevitably associated with a good N performance. In this context, the study provided new knowledge on the significant effects of regional, farm structural, agronomic and socio-economic characteristics on N performance, which also enables the identification of structural patterns and strategies to reduce N waste. Apart from constant site conditions such as altitude or soil fertility, factors that are more likely to be altered in the shorter term, just like selection and diversity of crops or choice of production type, also show an effect on increasing efficiency and reducing N waste accordingly. 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 generally. 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, such as with consulting services or innovative manure management options. 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, this study revealed the effectiveness of selected policy schemes and access to farm advice in moving towards balanced N management, justifying policy measures promoting sustainable farming.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

We thank Jonas Schmitt for providing complementary data, Christoph Duden for valuable comments on processing the data, Klaus Dittert, Meike Wollni and Anna Jacobs for valuable comments on the methodological approach, and Mareike Söder for valuable comments on revising the manuscript. We would like to thank the editor and two anonymous reviewers for their helpful remarks and suggestions, which have significantly improved the manuscript.

Appendix A. 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	
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	Sugar beet
Potato yield	continual	kg N/ha	Potato
Grassland yield	continual	kg N/ha	Permanent and temporary grassland, pasture, clovers
Vegetable area (factor)	continual	ha/ha	Cabbage, leafy vegetables, tuber vegetables, tomato, asparagus, other vegetables
Grain legumes yield	continual	kg N/ha	Field bean, pea, soy, energy protein plants, other pulse
Other crops area (factor)	continual	ha/ha	Sunflower, other oilseed, flax, fibre plant, tobacco plant, spice plant, others
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)

(*continued on next page*)

Table A1 (*continued*)

Variables investigated	Type	Unit	Description
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
Overview of the sectoral, manure application-specific and farm type-specific results of the advanced multiple regression model for the Nitrogen balance (N balance) and Nitrogen use efficiency (NUE) on farm level (n = 5923).

Independent variables	Description	Unit	Dependent variables: All – N balance (kg N/ha)	All – NUE (%)	Scale type: Organic N application < 50 kg N/ha – N balance (kg N/ha)	< 50 kg N/ha – NUE (%)	> 50 kg N/ha – N balance (kg N/ha)	> 50 kg N/ha – NUE (%)	Farm type: Arable, permanent – N balance (kg N/ha)	Arable, permanent – NUE (%)	Animals, mixed – N balance (kg N/ha)	Animals, mixed – NUE (%)
			Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
Region												
Large geographic regions	South	0: no; 1: yes	−8.5*	2.9*	−6.7*	5.0	−14.2*	0.3	−6.8*	6.1	−12.0*	1.5
	East	0: no; 1: yes	−9.0*	2.3*	−12.0*	9.0*	−8.9*	−2.3*	−14.1*	10.5*	−8.6*	−0.5
	West	0: no; 1: yes	0.5	−0.4	−7.4*	6.3*	1.5	−2.2*	−7.1*	5.2	1.4	−1.5
	North	0: no; 1: yes										
Natural yield potential	low	0: no; 1: yes	4.7*	−1.8	4.0	−4.2	1.4	−0.4	4.2	−5.0	1.7	−1.3
	medium	0: no; 1: yes	3.4	−0.4	2.5	−2.7	0.7	0.6	5.0*	−5.9*	−0.1	0.1
	high	0: no; 1: yes										
Altitude	low	0: no; 1: yes	16.9*	−4.2*	1.4	−4.3	12.3*	−5.7*	3.7	2.5	12.6*	−4.8*
	medium	0: no; 1: yes	19.2*	−8.0*	3.8	−5.2	17.7*	−7.9*	3.1	2.7	17.3*	−7.6*
	high	0: no; 1: yes										
Irrigated area (factor)		ha/ha	10.2	−1.3	12.2	−2.7	−7.1	6.7	5.5	5.6	25.8	−4.3
Farm structural												
Organic manure - cattle		kg N/ha	0.9*	−0.3*	0.7*	−0.4*	0.7*	−0.2*	0.7*	−0.7*	0.7*	−0.2*
Organic manure - pig		kg N/ha	0.8*	−0.2*	1.2*	−0.8*	0.8*	−0.1*	1.2*	−0.3*	0.8*	−0.1*
Organic manure - poultry		kg N/ha	1.1*	−0.2*	1.7*	−0.8*	1.0*	−0.1*	0.8*	−0.2	1.0*	−0.1*
Organic manure - other animals		kg N/ha	0.5*	−0.4*	0.6	−1.1*	0.5*	−0.2*	1.1*	−1.6*	0.4*	−0.2*
Organic manure - digestate		kg N/ha	0.6*	−0.2*	0.4*	−0.3*	0.4*	0.0	0.8*	−0.6*	0.5*	−0.1*
Wheat yield		kg N/ha	0.0	0.2*	−0.1*	0.3*	0.1*	0.1*	−0.1*	0.2*	0.1	0.2*
Rye yield		kg N/ha	−0.1	0.3*	0.0	0.2	−0.2	0.3*	−0.1	0.1	−0.2	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	0.1	0.2*	−0.3*	0.4*	0.3*	0.0	−0.3*	0.3*	0.3*	0.1
Maize yield		kg N/ha	−0.3*	0.3*	−0.8*	0.8*	0.1*	0.2*	−0.9*	0.8*	0.1*	0.2*
Rapeseed yield		kg N/ha	0.1	0.4*	0.1	0.2*	0.2	0.3*	0.0	0.2	0.3*	0.3*
Sugar beet yield		kg N/ha	−0.3*	0.5*	−0.3*	0.4*	−0.3	0.4*	−0.4*	0.4*	−0.4*	0.4*
Potato yield		kg N/ha	0.0	0.3*	−0.3*	0.3*	0.3*	0.2*	−0.3*	0.1	0.3*	0.2*
Grassland yield		kg N/ha	−0.2*	0.1*	−0.3*	−0.1	0.1*	0.1*	−0.3*	0.3	0.1*	0.1*
Vegetable area (factor)		ha/ha	14.4	26.0*	−4.5	60.3*	−7.6	44.6*	3.8	38.6*	−61.7	73.5*
Grain legumes yield		kg N/ha	−0.1	0.1	−0.3	0.6*	0.1	−0.1*	−0.4*	0.5*	0.3	−0.1

(*continued on next page*)

Table A2 (*continued*)

Independent variables	Description	Unit	Dependent variables: *All*		Scale type: *Organic N application*				*Farm type*			
					< 50 kg N/ha		*> 50 kg N/ha*		*Arable, permanent*		*Animals, mixed*	
			N balance	**NUE**	**N balance**	**NUE**	**N balance**	**NUE**	**N balance**	**NUE**	**N balance**	**NUE**
			(kg N/ha)	(%)	(kg N/ha)	(%)	(kg N/ha)	(%)	(kg N/ha)	(%)	(kg N/ha)	(%)
			Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
Other crops area (factor)		ha/ha	18.3*	3.2	−19.8*	29.9*	40.1	−0.4	−17.3*	18.3*	29.7	−0.5
Crop diversity	low	0: no; 1: yes	−13.0*	4.5*	−9.2*	0.8	−13.2*	2.0*	−5.4	1.9	−13.1*	3.4*
	medium	0: no; 1: yes	−2.9	1.5*	−4.7*	2.0	−3.6	−0.2	−1.2	0.1	−3.6	1.0
	high	0: no; 1: yes										
Production type	organic	0: no; 1: yes	−22.4*	3.4*	−28.3*	20.7*	−19.7*	1.2	−26.1*	26.8*	−19.0*	1.1
	conventional	0: no; 1: yes										
Socio-economic												
Farm size	low	0: no; 1: yes	−8.4*	3.2*	−7.9*	3.7	−4.7	2.9*	−11.5*	2.9	−2.5	2.5*
	medium	0: no; 1: yes	−3.2	0.6	−4.6	0.0	−0.7	−0.1	−8.5*	1.0	1.4	−0.3
	high	0: no; 1: yes										
Age	low	0: no; 1: yes	3.6	−2.8*	6.1	−8.4*	0.7	0.1	3.8	−6.2	2.4	−0.3
	medium	0: no; 1: yes	1.3	−1.3*	1.1	−3.1	1.0	−0.2	1.9	−2.2	0.6	−0.4
	high	0: no; 1: yes										
School education	low	0: no; 1: yes	−2.1	1.0	−2.3	3.1	−6.6	0.9	−0.8	3.6	−5.9	1.8
	medium	0: no; 1: yes	−5.2*	2.7*	−5.0*	4.1	−10.9*	1.5	−3.6	3.9	−9.5*	3.0*
	high	0: no; 1: yes										
Agricultural education	low	0: no; 1: yes	−1.1	0.7	−1.6	1.8	−1.6	−0.5	0.7	1.0	−2.4	−0.3
	medium	0: no; 1: yes	−3.9*	0.2	2.0	−2.3	−8.0*	0.6	2.1	−2.8	−7.9*	0.5
	high	0: no; 1: yes										
Operating profit	low	0: no; 1: yes	10.4*	−5.8*	4.3	0.9	15.9*	−6.9*	9.9*	−5.3	11.4*	−6.5*
	medium	0: no; 1: yes	4.4*	−3.2*	0.3	3.3	7.8*	−3.8*	4.3	−2.0	6.0*	−3.8*
	high	0: no; 1: yes										
Consulting services	low	0: no; 1: yes	9.2*	−2.5*	3.0	−3.6	13.6*	−1.0	0.1	−1.7	13.6*	−1.7*
	high	0: no; 1: yes										
Payments for AECM[1]		€/ha	−0.02*	0.01*	−0.01	0.01	−0.04*	0.00	−0.01	0.00	−0.04*	0.01
Compensation received		€/ha	−0.04	0.00	−0.04	0.08*	−0.04	0.00	−0.03	0.07	−0.05	0.00
Machinery and external services		€/ha	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Number of employees		heads	0.13*	−0.09*	0.12*	−0.17*	0.45*	0.01	0.10	−0.16*	0.38*	0.01
Observations		n	5923	5923	2478	2478	3445	3445	1932	1932	3991	3991
Goodness of fit		R^2	0.45	0.23	0.19	0.09	0.37	0.22	0.18	0.06	0.41	0.18

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
Overview of the 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	−8.8*	2.7*
	East	0: no; 1: yes	−8.8*	2.4*
	West	0: no; 1: yes	0.7	−0.2
	North	0: no; 1: yes		
Natural yield potential	low	0: no; 1: yes	5.2*	−1.7
	medium	0: no; 1: yes	3.7	−0.3
	high	0: no; 1: yes		
Altitude	low	0: no; 1: yes	16.0*	−4.4*
	medium	0: no; 1: yes	18.8*	−7.9*
	high	0: no; 1: yes		
Irrigated area (factor)		ha/ha	9.4	−1.8
Farm structural				
Organic manure - cattle	low	kg N/ha	0.80*	−0.34*
	medium	kg N/ha	0.81*	−0.34*
	high	kg N/ha	0.90*	−0.29*
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	0.5*	−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	0.0	0.1*
Spring grain yield		kg N/ha	0.1	0.2*
Maize yield		kg N/ha	−0.3*	0.3*
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	−0.2*	0.1*
Vegetable area (factor)		ha/ha	11.2	23.0*
Grain legumes yield		kg N/ha	−0.2	0.0
Other crops area (factor)		ha/ha	16.5*	1.8
Crop diversity	low	0: no; 1: yes	−14.2*	3.9*
	medium	0: no; 1: yes	−3.7*	1.1
	high	0: no; 1: yes		
Production type	ecological	0: no; 1: yes	−21.5*	3.8*
	conventional	0: no; 1: yes		
Socio-economic				
Farm size	low	0: no; 1: yes	−8.2*	3.3*
	medium	0: no; 1: yes	−3.1	0.6
	high	0: no; 1: yes		
Age	low	0: no; 1: yes	3.5	−2.8*
	medium	0: no; 1: yes	1.2	−1.4*
	high	0: no; 1: yes		
School education	low	0: no; 1: yes	−2.1	1.1
	medium	0: no; 1: yes	−5.2*	2.7*
	high	0: no; 1: yes		
Agricultural education	low	0: no; 1: yes	−1.1	0.7
	medium	0: no; 1: yes	−3.8*	0.2
	high	0: no; 1: yes		
Operating profit	low	0: no; 1: yes	11.3*	−5.5*
	medium	0: no; 1: yes	5.3*	−2.7*
	high	0: no; 1: yes		
Consulting services	low	0: no; 1: yes	9.1*	−2.5*
	high	0: no; 1: yes		
Payments for AECM[1]		€/ha	−0.02*	0.01*
Compensation received		€/ha	−0.04	0.00
Machinery and external services		€/ha	0.00	0.00
Number of employees		heads	0.13*	−0.09*
Observations		n	5923	5923
Goodness of fit		R^2	0.45	0.23

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

Table A4
Overview of the 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	−8.5*	2.9*
	East	0: no; 1: yes	−8.7*	2.1*
	West	0: no; 1: yes	0.3	−0.3
	North	0: no; 1: yes		
Natural yield potential	low	0: no; 1: yes	4.8*	−1.9*
	medium	0: no; 1: yes	3.6	−0.5
	high	0: no; 1: yes		
Altitude	low	0: no; 1: yes	16.9*	−4.4*
	medium	0: no; 1: yes	19.2*	−8.2*
	high	0: no; 1: yes		
Irrigated area (factor)		ha/ha	10.4	−1.4
Farm structural				
Organic manure - cattle		kg N/ha	0.9*	−0.3*
Organic manure - pig	low	kg N/ha	1.13*	−0.35*
	medium	kg N/ha	0.92*	−0.26*
	high	kg N/ha	0.83*	−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	0.0	0.2*
Spring grain yield		kg N/ha	0.1	0.2*
Maize yield		kg N/ha	−0.3*	0.3*
Rapeseed yield		kg N/ha	0.1	0.4*
Sugar beet yield		kg N/ha	−0.3*	0.5*
Potato yield		kg N/ha	0.0	0.3*
Grassland yield		kg N/ha	−0.2*	0.1*
Vegetable area (factor)		ha/ha	14.4	24.3*
Grain legumes yield		kg N/ha	−0.1	0.1
Other crops area (factor)		ha/ha	18.7*	3.0
Crop diversity	low	0: no; 1: yes	−12.9*	4.4*
	medium	0: no; 1: yes	−2.7	1.5*
	high	0: no; 1: yes		
Production type	ecological	0: no; 1: yes	−22.3*	3.3*
	conventional	0: no; 1: yes		
Socio-economic				
Farm size	low	0: no; 1: yes	−8.7*	3.3*
	medium	0: no; 1: yes	−3.4	0.8
	high	0: no; 1: yes		
Age	low	0: no; 1: yes	3.4	−2.8*
	medium	0: no; 1: yes	1.3	−1.3*
	high	0: no; 1: yes		
School education	low	0: no; 1: yes	−1.8	0.8
	medium	0: no; 1: yes	−5.1	2.6*
	high	0: no; 1: yes		
Agricultural education	low	0: no; 1: yes	−0.9	0.6
	medium	0: no; 1: yes	−3.9*	0.3
	high	0: no; 1: yes		
Operating profit	low	0: no; 1: yes	10.2*	−5.7*
	medium	0: no; 1: yes	4.0*	−2.9*
	high	0: no; 1: yes		
Consulting services	low	0: no; 1: yes	9.2*	−2.5*
	high	0: no; 1: yes		
Payments for AECM[1]		€/ha	−0.02*	0.01*
Compensation received		€/ha	−0.04	0.00
Machinery and external services		€/ha	0.00	0.00
Number of employees		heads	0.13*	−0.09*
Observations		n	5923	5923
Goodness of fit		R^2	0.45	0.23

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

Table A5
Overview of the Nitrogen use efficiency (NUE) values at farm level under consideration of biological Nitrogen fixation on grassland based on mineral fertiliser intensity and of externalised Nitrogen from purchased feed and sold manure with different levels of external Nitrogen efficiency, and combination of lowest and highest assumptions (n = 5923).

Scale type	Sample size (n)	Indicator	Baseline	BNF grassland[1]	Externalities							
					Feed import N efficiency			Manure export N efficiency			Combined	
					High[2]	Medium[3]	Low[4]	High[5]	Medium[6]	Low[7]	High[8]	Low[9]
All	5923	NUE (%) median	60	60	50	46	42	60	60	60	50	42
Arable	1522	NUE (%) median	96	96	96	94	93	96	96	96	96	93
Dairy	1744	NUE (%) median	41	41	31	27	23	42	41	40	31	23
Other cattle	573	NUE (%) median	55	53	47	42	39	55	55	55	48	39
Pig, poultry	543	NUE (%) median	51	51	36	31	26	52	50	49	37	25
Permanent	410	NUE (%) median	115	115	115	115	115	115	115	115	115	115
Mixed	1129	NUE (%) median	60	60	52	50	46	61	60	60	52	46

[1] *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.*
[2] *NUE of 60% is assumed for purchased feed.*
[3] *NUE of 50% is assumed for purchased feed.*
[4] *NUE of 40% is assumed for purchased feed.*
[5] *NUE of 50% is assumed for sold manure.*
[6] *NUE of 30% is assumed for sold manure.*
[7] *NUE of 20% is assumed for sold manure.*
[8] *NUE of 60% is assumed for purchased feed, NUE of 50% is assumed for sold manure.*
[9] *NUE of 40% is assumed for purchased feed, NUE of 20% is assumed for sold manure.*

References

Amelung, W., Blume, H.-P., Fleige, H., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.-M., 2018. Scheffer/Schachtschabel Lehrbuch der Bodenkunde, 17. Aufl. 2018. Springer Spektrum, Berlin, Heidelberg.

Amon, B., Borghardt, G., Düsing, D., Elberskirch, K., Eurich-Menden, B., Hahne, J., Hartung, E., Hofmeier, M., Kowalewsky, H.-H., Neser, S., Pflanz, W., Pries, M., Richter, S., Schmidhalter, U., Schrader, L., Spiekers, H., Stalljohann, G., Wulf, S., 2021. Ammoniakemissionen in der Landwirtschaft mindern: Gute fachliche Praxis. Dessau-Roßlau, UBA.

Bach, M., 2013. Regionalisierung des Stickstoff-Überschuss einzelbetrieblicher Hoftorbilanzen (Beispiel Hessen): Überlegungen zur methodischen Weiterentwicklung der N-Bilanzierung.

Bach, M., Häußermann, U., Klement, L., Knoll, L., Breuer, L., Weber, T., Fuchs, S., Heldstab, J., Reutimann, J., Schnäppi, B., 2020. *Reaktive Stickstoffflüsse in Deutschland 2010–2014 (DESTINO Bericht 2): Abschlussbericht*, Dessau-Roßlau.

Barreiro Hurle, J., Bogonas, M., Himics, M., Hristov, J., Perez Dominguez, I., Sahoo, A., Salputra, G., Weiss, F., Baldoni, E., Elleby, C., 2021. Modelling Environmental and Climatic Ambition in the Agricultural Sector with the CAPRI Model: Exploring the Potential Effects of Selected Farm to Fork and Biodiversity Strategies Targets in the Framework of the 2030 Climate Targets and the Post 2020 Common Agricultural Policy. Publications Office of the European Union, Luxemburg.

BMEL, 2018. Buchführung der Testbetriebe: Grundlagen zur BMEL-Testbetriebsbuchführung. https://www.bmel-statistik.de/fileadmin/daten/BFB-0114001-2018.pdf. Accessed 7/21/2022.

BMEL, 2022a. Allgemeine Preisstatistik: Preise für landwirtschaftliche Betriebsmittel. https://www.bmel-statistik.de/preise/allgemeine-preisstatistik. Accessed 4/28/2022.

BMEL, 2022b. BMEL macht den ökologischen Landbau zu seinem Leitbild für eine nachhaltige Landwirtschaft: Pressemitteilung Nr. 5/2022. https://www.bmel.de/SharedDocs/Pressemitteilungen/DE/2022/05-oekolandbau-bekanntmachungen.html. Accessed 7/22/2022.

BMEL, 2022c. Landwirtschaft. Testbetriebsnetz. https://www.bmel-statistik.de/landwirtschaft/testbetriebsnetz. Accessed 7/21/2022.

Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: harnessing ecosystem services for food security. Trends Ecol. Evol. 28 (4), 230–238.

Bremmer, J., Gonzalez-Martinez, A., Jongeneel, R., Huiting, H., Stokkers, R., Ruijs, M., 2021. Impact Assessment of EC 2030 Green Deal Targets for Sustainable Crop Production, p. 97894644.

Buckley, C., Wall, D.P., Moran, B., O'Neill, S., Murphy, P.N.C., 2016. Farm gate level nitrogen balance and use efficiency changes post implementation of the EU nitrates directive. Nutr. Cycl. Agroecosyst. 104 (1), 1–13.

Cassman, K., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Undefined*.

Chmelíková, L., Schmid, H., Anke, S., Hülsbergen, K.-J., 2021. Nitrogen-use efficiency of organic and conventional arable and dairy farming systems in Germany. Nutr. Cycl. Agroecosyst. 1–18.

Conradt, S., Bokusheva, R., Finger, R., Kussaiynov, T., 2017. Yield Trend Estimation in the Presence of Farm Heterogeneity and Non-linear Technological Change.

Dachbrodt-Saaydeh, S., Sellmann, J., Roßberg, D., 2019. Cluster zur regionalen Erhebung und Analyse der Pflanzenschutzintensität (CEPI) im Ackerbau. J. Kult. 71 (10), 264–270.

De Vries, W., Schulte-Uebbing, L., 2020. Required Changes in Nitrogen Inputs and Nitrogen Use Efficiency to Reconcile Agricultural Productivity with Water an Air Quality Objectives in the EU-27. International Fertiliser Society, Cambridge, UK (842).

DESTATIS, 2022a. Importpreise im April 2022: +31,7% gegenüber April 2021: Pressemitteilung Nr. 218 vom 30. Mai 2022 https://www.destatis.de/DE/Presse/Pressemitteilungen/2022/05/PD22_218_614.html. Accessed 5/31/2022.

DESTATIS, 2022b. Strukturwandel in der Landwirtschaft hält an: Pressemitteilung Nr. 028 vom 21. Januar 2021. *Statistisches Bundesamt*.

Dise, N.B., Ashmore, M., Belyazid, S., Bleeker, A., Bobbink, R., De Vries, W., Erisman, J. W., Spranger, T., Stevensand, C.J., Van den Berg, L., 2011. Nitrogen as a threat to European terrestrial biodiversity. In: Sutton, M.A. (Ed.), The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge Univ. Press, Cambridge, pp. 463–494.

Duden, C., Offermann, F., 2020. Income risk of German farms and its drivers. German J. Agricult. Econ. 69 (2).

Duden, C., Urban, J., Offermann, F., Hirschauer, N., 2019. Die Wirkung von Ertrags- und Wetterindexversicherungen auf das Erfolgsrisiko deutscher Ackerbaubetriebe – wird die Hedgingeffektivität überschätzt? Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft. Aktuelle Beiträge, Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft.

DüV, 2020. Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim. Düngen, Düngeverordnung.

DWD, 2022. Deutscher Wetterdienst. CDC - Climate Data Center: Current version: CDC-v2.1.b22.09. https://cdc.dwd.de/portal/. Accessed 12/15/2022.

Ebert, V., Paustian, M., Strecker, O., Kosiolek, E., Völker, J., 2018. Evaluation und Optimierung der landwirtschaftlichen Gewässerschutzberatung zur Umsetzung der europäischen Wasserrahmenrichtlinie in Nordrhein-Westfalen, Bonn.

Ehrmann, M., 2017. Modellgestützte Analyse von Einkommens- und Umweltwirkungen auf Basis von Testbetriebsdaten, Braunschweig.

EUNEP, 2015. Nitrogen Use Efficiency (NUE) - an indicator for the Utilization of Nitrogen in Agriculture and Food Systems. European Union Nitrogen Expert Panel.

European Commission, 2021. The Farm Sustainability Data Network (FSDN): Outcomes of the consultation process and discussions on possible concrete improvements of FADN in 2022. https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/summary-second-fsdn-workshop_en.pdf. Accessed 7/14/2022.

European Commission, 2022. Farm to Fork strategy for a fair, healthy and environmentally-friendly food system. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en. Accessed 10/11/2022.

Eurostat, 2013. Nutrient Budgets – Methodology and Handbook. Version 1.02. https://ec.europa.eu/eurostat/documents/2393397/2518760/Nutrient_Budgets_Handbook_%28CPSA_AE_109%29_corrected3.pdf/4a3647de-da73-4d23-b94b-e2b23844dc31. Accessed 12/2/2022.

Finger, R., 2010. Revisiting the Evaluation of robust regression techniques for crop yield data Detrending.

Gamer, W., Bahrs, E., 2010. Bilanzen von potenziell umweltbelastenden Nährstoffen (N, P, K und S) der Landwirtschaft in Baden-Württemberg: Ergebnistabellen, Stuttgart-Hohenheim.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Agriculture. Sustainable intensification in agriculture: premises and policies. Science 341 (6141), 33–34.

German Environment Agency, 2023. Hintergrundbelastungsdaten Stickstoff. Ergebnisse und Daten des PINETI-3-Projekts. https://gis.uba.de/website/depo1/. Accessed 7/18/2023.

German Federal Government, 2019. Climate Action Programme 2030: Climate Protection Program 2030 of the German Federal Government for the Implementation of the Climate Protection Plan 2050. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

German Federal Government, 2021. German Sustainable Development Strategy: Update 2021. Publikationsversand der Bundesregierung, Rostock.

Geupel, M., Richter, S., Schlesinger, L., 2021. Stickstoff - Element mit Wirkung. Ein integrierter Zielwert setzt einen neuen Rahmen, Dessau-Roßlau.

Godfray, H.C.J., Garnett, T., 2014. Food security and sustainable intensification. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 369 (1639), 20120273.

Godinot, O., Leterme, P., Vertès, F., Faverdin, P., Carof, M., 2015. Relative nitrogen efficiency, a new indicator to assess crop livestock farming systems. Agron. Sustain. Dev. 35 (2), 857–868.

Gourley, C.J.P., Dougherty, W.J., Weaver, D.M., Aarons, S.R., Awty, I.M., Gibson, D.M., Hannah, M.C., Smith, A.P., Peverill, K.I., 2012. Farm-scale nitrogen, phosphorus, potassium and sulfur balances and use efficiencies on Australian dairy farms. Anim. Prod. Sci. 52 (10), 929.

Hansen, H., Bahta, S., Offermann, F., 2009. The Statistical Usefulness of the EU FADN Database for Production Cost Estimations: FACEPA Deliverable No. D1.3, Braunschweig.

Haß, M., Banse, M., Deblitz, C., Freund, F., Geibel, I., Gocht, A., Kreins, P., Laquai, V., Offermann, F., Osterburg, B., Pelikan, J., Rösemann, C., Salamon, P., Zinnbauer, M., Zirngibl, M.-E., 2020. Thünen-Baseline 2020–2030: Agrarökonomische Projektionen für Deutschland. Johann Heinrich von Thünen-Institut.

Isermeyer, F., Nieberg, H., Banse, M., 2020. Auswirkungen aktueller Politikstrategien (Green Deal, Farm-to-Fork, Biodiversitätsstrategie 2030; Aktionsprogramm Insektenschutz) auf Land- und Forstwirtschaft sowie Fischerei. Deutsche Nationalbibliothek.

Jan, P., Calabrese, C., Lips, M., 2017. Determinants of nitrogen surplus at farm level in Swiss agriculture. Nutr. Cycl. Agroecosyst. 109 (2), 133–148.

Kelm, M., Loges, R., Taube, F., 2007. N-Bilanzen ökologischer und konventioneller Praxisbetriebe in Norddeutschland - Ergebnisse aus dem Projekt COMPASS. In: Zikeli, S., Claupein, W., Dabbert, S., Kaufmann, B., Müller, T., Valle Zarate, A. (Eds.), Zwischen Tradition und Globalisierung. Beiträge zur 9. Wissenschaftstagung Ökologischer Landbau. Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten (VDLUFA), pp. 25–28.

Klages, S., Osterburg, B., Hansen, H., 2017. Betriebliche Stoffstrombilanzen für Stickstoff und Phosphor - Berechnung und Bewertung Dokumentation der Ergebnisse der Bund-Länder-Arbeitsgruppe "Betriebliche Stoffstrombilanzen" und der begleitenden Analysen des Thünen-Instituts.

Klages, S., Heidecke, C., Osterburg, B., Bailey, J., Calciu, I., Casey, C., Dalgaard, T., Frick, H., Glavan, M., D'Haene, K., Hofman, G., Leitão, I., Surdyk, N., Verloop, K., Velthof, G., 2020. Nitrogen surplus—a unified Indicator for water pollution in Europe? Water 12 (4), 1197.

KTBL, 1992. KTBL-Taschenbuch Landwirtschaft. Daten für die Betriebskalkulation in der Landwirtschaft, 16th edn. BLV Verlagsgesellschaft mbH, München.

Kuka, K., Lehn, F., Leitans, L., Astover, A., Eriksson, A.K., Listh, U., Salo, T., Luostarinen, S., Helin, J., Lehtonen, E., Wach, D., Skowron, P., Kaasinen, S., Kozlova, N., Borsting, C., Ribikauskas, V., 2019. National Nutrient Balances in the Baltic Sea Region. Interreg Baltic Sea Region Project Manure Standards.

Latacz-Lohmann, U., Balmann, A., Birner, R., Christen, O., Gauly, M., Grajewski, R., Grethe, H., Martinez, J., Nieberg, H., Pischetsrieder, M., Renner, B., Röder, N., Schmid, J.C., Spiller, A., Taube, F., Voget-Kleschin, L., Weingarten, P., 2019. Zur effektiven Gestaltung der Agrarumwelt- und Klimaschutzpolitik im Rahmen der Gemeinsamen Agrarpolitik der EU. *Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft* (227).

LfL, 2019. Basisdaten für die Umsetzung der Düngeverordnung, für die Beratung und Planung, zur Berechnung des Düngebedarfs, des Nährstoffvergleichs, der 170 kg Grenze Ngesamt, des Lageraums für organische Dünger. der Stoffstrombilanz, Freising.

LfL, 2022. Gründlandverbesserung. Bayerische Eiweißinitiative. https://www.lfl.bayern.de/schwerpunkte/eiweissstrategie/158735/index.php. Accessed 10/27/2022.

Löw, P., Karatay, Y.N., Osterburg, B., 2020. Nitrogen use efficiency on dairy farms with different grazing systems in northwestern Germany. Environ. Res. Commun. 2 (10), 105002.

Löw, P., Osterburg, B., Garming, H., Neuenfeldt, S., Schultheiß, U., 2021a. Bericht über die Auswirkungen der verbindlichen Stoffstrombilanzierung. Deutscher Bundestag, Berlin.

Löw, P., Osterburg, B., Klages, S., 2021b. Comparison of regulatory approaches for determining application limits for nitrogen fertilizer use in Germany. Environ. Res. Lett. 16 (5), 55009.

Machmüller, A., Sundrum, A., 2019. Nitrogen-mass flows and balances of dairy farms in the context of the German fertilizer ordinance. Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft.

Nieberg, H., von Münchhausen, H.F., 1996. Zusammenhang zwischen Betriebsgröße und Umweltverträglichkeit der Agrarproduktion – empirische Ergebnisse aus den alten und neuen Bundesländern. *Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues e.V*, 32, pp. 129–140.

Nimmo, J., Lynch, D.H., Owen, J., 2013. Quantification of nitrogen inputs from biological nitrogen fixation to whole farm nitrogen budgets of two dairy farms in Atlantic Canada. Nutr. Cycl. Agroecosyst. 96 (1), 93–105.

Oenema, O., 2015. Nitrogen use efficiency (NUE): an indicator for the utilisation of nitrogen in agricultural and food systems. Int. Fertiliser Soc. 773.

Ondersteijn, C., Beldman, A., Daatselaar, C., Giesen, G., Huirne, R., 2003. Farm structure or farm management: effective ways to reduce nutrient surpluses on dairy farms and their financial impacts. Livest. Prod. Sci. 84 (2), 171–181.

Oosterhoff, J., 1994. Trimmed mean or sample median? Stat. Prob. Lett. 20 (5), 401–409.

Osterburg, B., 2007. Analysen zur Wirkung von Agrarumweltzahlungen auf die Senkung von N-Salden. In: *Maßnahmen zur Reduzierung von Stickstoffeinträgen in Gewässer - eine wasserschutzorientierte Landwirtschaft zur Umsetzung der Wasserrahmenrichtlinie*. Landbauforschung Völkenrode, pp. 253–266.

Parris, K., 1998. Agricultural nutrient balances as Agri-environmental indicators: an OECD perspective. Environ. Pollut. 102 (1), 219–225.

Powell, J.M., Gourley, C., Rotz, C.A., Weaver, D.M., 2010. Nitrogen use efficiency: a potential performance indicator and policy tool for dairy farms. Environ. Sci. Pol. 13 (3), 217–228.

Prokopy, L.S., Floress, K., Klotthor-Weinkauf, D., Baumgart-Getz, A., 2008. Determinants of agricultural best management practice adoption: evidence from the literature. J. Soil Water Conserv. 63 (5), 300–311.

Quemada, M., Lassaletta, L., Jensen, L.S., Godinot, O., Brentrup, F., Buckley, C., Foray, S., Hvid, S.K., Oenema, J., Richards, K.G., Oenema, O., 2020. Exploring nitrogen indicators of farm performance among farm types across several European case studies. Agric. Syst. 177, 102689.

Raghuram, N., Sutton, M.A., Jeffery, R., Ramachandran, R., Adhya, T.K., 2021. From South Asia to the world: embracing the challenge of global sustainable nitrogen management. One Earth 4 (1), 22–27.

Reinsch, T., Loza, C., Malisch, C.S., Vogeler, I., Kluß, C., Loges, R., Taube, F., 2021. Toward specialized or integrated systems in Northwest Europe: on-farm eco-efficiency of dairy farming in Germany. Front. Sustain. Food Syst. 5, 167.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461 (7263), 472–475.

Scheringer, J., 2002. Nitrogen on Dairy Farms: Balances and Efficiency. Göttinger Agrarwissenschaftliche Beiträge.

Schmitt, J., Offermann, F., Söder, M., Frühauf, C., Finger, R., 2022. Extreme weather events cause significant crop yield losses at the farm level in German agriculture. Food Policy 112, 102359.

Schneider, S., Brunlehner, E.-M., Spiekers, H., 2021. Nährstoffkreislauf in Schweinebetrieben: Ergebnisse und gesamtbetriebliche Beratungsansätze aus dem Verbundprojekt "demonstration farms". Züchtungskunde 93, 19–41.

Schreiber-Gregory, D.N., 2017. Multicollinearity what is it why should we care and how can it be controlled? Henry M Jackson Foundation, National University (paper 1404-2017).

Schulte-Uebbing, L., Beusen, A., Bouwman, A., de Vries, W., 2022. From planetary to regional boundaries for agricultural nitrogen pollution. Nature 610 (7392), 507–512.

SPD, DIE GRÜNEN, FDP, 2021. Mehr Fortschritt wagen. Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit.

STMELF, STMUV, 2022. Wasserpakt. Vereinbarung zum kooperativen Gewässerschutz mit der Landwirtschaft. *Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten; Bayerisches Staatsministerium für Umwelt und Verbraucherschutz*.

StoffBilV, 2017. Verordnung über den Umgang mit Nährstoffen im Betrieb und betrieblichen Stoffstrombilanzen: Stoffstrombilanzverordnung.

Sutton, M.A., Bleeker, A., 2013. Environmental science: the shape of nitrogen to come. Nature 494 (7438), 435–437.

Tian, X., Engel, B.A., Qian, H., Hua, E., Sun, S., Wang, Y., 2021. Will reaching the maximum achievable yield potential meet future global food demand? J. Clean. Prod. 294, 126285.

UNEP, 2019. United Nations Environment Assembly of the United Nations Environment Programme Fourth session: Resolution adopted by the United Nations Environment Assembly on 15 March 2019, Nairobi. *United Nations* (EA.4/Res.14).

Urban, D., Mayerl, J., 2018. *Angewandte Regressionsanalyse: Theorie, Technik und Praxis,* 5, überarbeitete Auflage. Springer VS, Wiesbaden.

Uthes, S., 2022. Einfluss steigender Energiepreise auf den Düngemitteleinsatz. *ZALF Opinion Paper* (1/22).
Westhoek, H., Lesschen, J.P., Leip, A., Rood, T., Wagner, S., de Marco, A., Murphy-Bokern, D., Pallière, C., Howard, C.M., Oenema, O., Sutton, M.A., 2015. Nitrogen on the Table: The Influence of Food Choices on Nitrogen Emissions and the European Environment. Edinburgh, UK.
Wilcox, R.R., 1996. A note on testing hypotheses about trimmed means. Biom. J. 38 (2), 173–180.
Wilcox, R.R., 2017. Introduction to Robust Estimation and Hypothesis Testing, Fourth edition. Academic Press, Amsterdam.
Winiwarter, W., Amon, B., Bodirsky, B.L., Friege, H., Geupel, M., Lassaletta, L., Raghuram, N., 2022. Focus on reactive nitrogen and the UN sustainable development goals. Environ. Res. Lett. 17 (5), 50401.
Zhang, X., Lassaletta, L., 2022. Manure management benefits climate with limits. Nat. Food 3, 312–313.
Zinnbauer, M., Eysholdt, M., Henseler, M., Herrmann, F., Kreins, P., Kunkel, R., Nguyen, H., Tetzlaff, B., Venohr, M., Wolters, T., Wendland, F., 2023. Quantifizierung aktueller und zukünftiger Nährstoffeinträge und Handlungsbedarfe für ein deutschlandweites Nährstoffmanagement - AGRUM-DE. Johann Heinrich von Thünen-Institut, Braunschweig.