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Agronomic analysis of nitrogen performance indicators in intensive arable cropping systems: An appraisal of big data from commercial farms

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ABSTRACT

Nitrogen (N) management is important for farmers to balance production, economic and environmental performance of their farms. This is particularly true in the intensive cropping systems of northwest Europe where tuber, root and bulb crops are cultivated in rotation with cereal crops and where an intensive livestock sector makes organic manures available at low cost for arable farmers. Here, we build upon a large database of farmer field data to assess mineral and organic fertiliser N performance, and its determinants, for the major arable crops in the Netherlands according to the guidelines provided by the EU N Expert Panel (EUNEP). The EUNEP framework quantifies N outputs and N inputs, N-use efficiency as the ratio between N outputs and N inputs (NUE in kg N output harvested per kg N input) and N surplus as the difference between N inputs and N outputs (Ns in kg N ha^{-1}). As a next step, biophysical and crop management determinants of N performance were explored using data from different years, soil types and N management in relation to the amount, source, time and method of N applied. NUE was on average ca. 0.95 kg N kg^{-1} N for seed potato, sugar beet and spring onion, 0.87 kg N kg^{-1} N for ware potato, ca. 0.80 kg N kg^{-1} N for starch potato and winter wheat and, ca. 0.70 kg N kg^{-1} N for spring barley, all within or above the target range of 0.50–0.90 kg N kg^{-1} N proposed by the EUNEP. Ns was on average below the EUNEP threshold of 80 kg N ha^{-1} for all crops: 78 kg N ha^{-1} for ware potato and winter wheat, ca. 70 kg N ha^{-1} for starch potato, ca. 50 kg N ha^{-1} for spring barley, ca. 25 kg N ha^{-1} for sugar beet and spring onion and less than 20 kg N ha^{-1} for seed potato. Although average Ns was below 80 kg N ha^{-1}, ca. 40% of the ware potato, starch potato and winter wheat fields analyzed had Ns above this threshold. The relatively high NUE combined with high Ns for most crops are the result of high N outputs (yields) combined with high N application rates. Moreover, high NUE and small Ns were mostly associated with smaller N application rates and with the use of mineral fertilisers instead of organic fertilisers, while there were no clear relationships between the two indicators on the one hand with N application time or method on the other. We conclude NUE and Ns were on average within the EUNEP target range for most crops, but there are still a considerable number of under-performing farms where increases in NUE and reductions in Ns are possible through reducing N inputs. We recommend future research to assess the benefits of organic fertilisers from a circularity perspective at regional and national levels and to cross-validate the crop-specific results presented in this study with NUE assessments at cropping systems level.

1. Introduction

Sustainable intensification provides the dominant paradigm to reconcile agricultural production on the one hand and environmental quality on the other (Garnett et al., 2013). This can be achieved through increases in resource-use efficiency as a result of yield gap closure and reductions in the need for, and use of, external inputs. Opportunities to achieve this are context-specific and depend on the relative importance

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of 'sustainability' and 'intensification' within the broader food security and environmental concerns at national level (Zhang et al., 2015; Lassaletta et al., 2014). For instance, a recent assessment of European countries showed that the Netherlands has the greatest gross-value added per unit of resource input or pollution (i.e., eco-efficiency), but also the largest environmental impact (van Grinsven et al., 2019).

Understanding the scope to balance productivity and sustainability of agricultural systems requires integrated frameworks, indicators and target values (Chukalla et al., 2020). These are helpful to define a 'safe operating space' for agricultural production and resource-use efficiency that also explicitly accounts for environmental performance (e.g., Quemada et al., 2020; Hunter et al., 2017; Zhang et al., 2015; Bommarco et al., 2013). Monitoring nitrogen (N) applications and flows are particularly important in this context as N plays a key role in crop production (Schröder, 2014; de Wit, 1992) and its mismanagement may lead to economic losses for farmers and substantial environmental impacts. The EU N Expert Panel (EUNEP) proposed a consistent and robust methodology to benchmark N performance in terms of N inputs, N outputs, N-use efficiency (NUE) and N surplus (Ns, EUNEP, 2015). NUE is defined as the ratio between the amount of N output in harvested products and the amount of N inputs applied with fertilisers and available from other sources (e.g., atmospheric deposition). Ns refers to the difference between N input and N output. Throughout this paper, NUE and Ns refer to total (not just 'plant available') N budget unless otherwise indicated.

Small marginal yield responses to applied N are commonly observed in the intensive cropping systems of Northwest Europe (e.g., Weiser et al., 2018; Silva et al., 2017), where nutrient application rates are well-above those observed in other parts of the world (Lassaletta et al., 2014). This is still true despite the sharp decline in nutrient application rates observed since the late 1980s, as a result of environmental regulations introduced to restrict N surpluses. Such regulations are still in place in countries like the Netherlands and are part of European legislation (van Grinsven et al., 2016; Schröder and Neeteson, 2008). While these may reduce input cost, they also pose challenges for farmers, who may fear that compliance with the regulations will jeopardize yield and farm income. Farmers' decisions regarding nutrient management must also consider efficient use of abundantly available organic fertilisers at cropping systems level (also in relation to phosphorus) and long-term impacts on soil fertility.

Experimental research is helpful to identify optimal N rates to balance production, efficiency and environmental emissions (e.g., Neeteson and Wadman, 1987), but is bound to a specific location and controlled conditions which are generally not achieved in farmers' fields. Alternatively, 'big data' (i.e., a high volume, velocity and variety of information to require specific analytical and technological methods for its transformation into value; de Mauro et al., 2016) from individual farmers can be combined with the NUE indicator proposed by the EUNEP to compare agricultural systems across regions (Quemada et al., 2020). This potentially allows establishing relationships between production, efficiency and emissions and provides an entry point to identify the determinants of NUE for a population of farmers and under actual crop and farm management.

The objective of this study was twofold: (1) to compare N output, N input, NUE and Ns for the major arable crops in the Netherlands according to the guidelines provided by the EUNEP, and (2) to investigate the determinants of N input, NUE and Ns for the main arable crops in the Netherlands. It is hypothesized that (a) both NUE and Ns are high for arable crops cultivated in the Netherlands compared to the targets proposed by the EUNEP and (b) the environmental sustainability and agronomic efficiency of these cropping systems can be improved by reducing N inputs. This study presents ranges of crop-specific NUE and Ns based on a large number of farmers' fields in the Netherlands (more than 10,000 crop field-year combinations) which contrasts with previous agronomic research mostly documenting results from trials conducted under controlled conditions. The insights derived from this analysis contribute to the knowledge base needed for sustainable N management that is attuned to local conditions.

2. Materials and methods

2.1. N performance indicators

2.1.1. Definition and quantification

NUE and Ns were quantified for the seven major arable crops in the Netherlands following the guidelines of the EUNEP (2015). NUE indicates how efficiently N is used (i.e., the amount of output produced per unit input) while Ns indicates potential N losses to the environment (i.e., difference between N input and N output). The indicator N emission intensity (NEI) was also estimated to assess the environmental impact per unit output (van Groenigen et al., 2010). Individual farmer field data were used to calculate these indicators while assuming the field as the spatial system boundary and the mass balance principle for N. These N indicators of farm performance were calculated as follows:

$$\text{N output}\,(\text{kg N ha}^{-1}) = \text{Ya} \times \text{N}_{\text{YIELD}} \tag{1}$$

$$\text{N input}\,(\text{kg N ha}^{-1}) = \text{Total N}_{\text{APPL}} + \text{N}_{\text{SEED}} + \text{N}_{\text{DEPO}} \tag{2}$$

$$\text{N-use efficiency (NUE, kg N kg}^{-1}\text{ N}) = \frac{\text{N output}}{\text{N input}} \tag{3}$$

$$\text{N surplus (Ns, kg N ha}^{-1}) = \text{N input} - \text{N output} \tag{4}$$

$$\text{N emission intensity }\left(\text{NEI, kg N kg}^{-1}\text{ N}\right) = \frac{\text{N surplus}}{\text{N output}} \tag{5}$$

where Ya and Total N_{APPL} stand for actual yield in farmers' fields (t fresh-matter, FM, ha^{-1}) and total N applied with mineral and organic fertilisers (kg N ha^{-1}), respectively. N_{YIELD} refers to the N concentration in the harvested product and has default values of 3.3 kg N t^{-1} FM for ware potato, 3.0 kg N t^{-1} FM for seed potato, 3.7 kg N t^{-1} FM for starch potato, 1.8 kg N t^{-1} FM for sugar beet, 2.2 kg N t^{-1} FM for spring onion, 17.3 kg N t^{-1} FM for winter wheat and, 13 kg N t^{-1} FM for spring barley (de Haan and van Geel, 2013). These N concentrations were adopted because they are the official values used to inform policy in the Netherlands. N in straw for wheat was not considered in the calculation of N output because collected data did not indicate whether straw was exported or retained. Total N_{APPL} refers to the amount of mineral and organic N applied (not corrected for replacement values) with both mineral and organic fertilisers during the growing season (see further details in Section 2.2.1). N_{SEED} is the amount of N in planting material, assumed to be 10.6 kg N ha^{-1} for potato, nil for sugar beet and spring onion, 3.5 kg N ha^{-1} for winter wheat and 2.5 kg N ha^{-1} for spring barley (www.agrimatie.nl). Finally, N_{DEPO} (kg N ha^{-1}) is the atmospheric N deposition, which was assumed to be 25 kg N ha^{-1} year^{-1} (MNC, 2014). N inputs available via irrigation water or water flows through capillary rise were not considered due to uncertainties in the irrigation water amounts applied, amounts of capillary supply from groundwater and in the corresponding N concentrations.

The N input conceptualized by the EUNEP (2015) considers both mineral and organic N applied (Eq. (2)). While we adopted that convention, it is recognised that not all N applied with organic manures will be available for crop uptake in the year of application. Fertiliser N replacement values were used to estimate the plant available N applied (PANA) from organic manures in the year of application, and to study the impact of these replacement values on NUE and Ns. The calculation of PANA in each field required different primary and secondary data, which were combined as follows:

$$\text{PANA}\ \left(\text{kg N ha}^{-1}\right) = \sum_{j=1}^{\text{type}} \sum_{s=1}^{\text{season}} \text{Fertiliser amount}_{js} \times \text{Ncont}_j \times \text{ReplValue}_{js} \quad (6)$$

where 'Fertiliser amount' (kg ha^{-1}) refers to the amount of mineral and organic fertiliser applied in a given field (as recorded in the database) with fertiliser type j in season s (autumn or spring). Ncont (kg kg^{-1}) refers to the concentration of N in each mineral and organic fertiliser type recorded in the database and these were cleaned and standardized prior to the analysis (Fig. A1). Finally, ReplValue (kg kg^{-1}) stands for the mineral fertiliser-N replacement value in the year of application assumed for each organic fertiliser type in a given season, values of which are provided in Table A5 (van Dijk et al., 2004). The replacement value of organic fertilisers refers to the equivalent effect of organic manures expressed in mineral fertiliser-N. Plant available N applied in each field was compared to the standard crop-specific recommendations for the Netherlands (Table A3), which were derived assuming the default spring mineral soil N stocks proposed by van Dijk and Schröder (2007).

The EUNEP framework assumes a steady state equilibrium between annual net mineralization from the soil N pool and the total annual N input into the soil N pool. Soil N mineralization is an internal process that should not appear on the N balance sheet (Quemada et al., 2020; EUNEP, 2015). Instead, in theory, possible deviations of actual soil N mineralization from an equilibrium value could be accounted for if such equilibrium was known. This, however, is not feasible for thousands of farmers' fields, and was not done in this study. N mineralization depends on the history of each field in terms of crop rotation, the use of organic manures and the management of crop residues or green manure crops. All previous studies that applied the EUNEP framework have consciously ignored actual net soil N mineralization, as we do here. Instead, we discuss in Section 4.3 the plausibility of the steady equilibrium assumption in the Netherlands, and possible implications for the results presented (see EUNEP, 2015). Although the equilibrium approach will be inaccurate for analysis of single fields, we argue it will approximately hold for a large set of fields of a particular soil-crop combination, and for sets of crops combined in a farm (i.e., crop rotation level).

2.1.2. Target values for N indicators

The target range for NUE (between 0.50 and 0.90 kg N kg^{-1} N) and threshold for Ns (80 kg N ha^{-1}) as proposed by the EUNEP (2015) were adopted in this study. Based on these values, it was possible to differentiate fields with high NUE (>0.90 kg N kg^{-1} N) characterized by possible mining of soil N in the long-run, fields with desired NUE ($0.50 \leq \text{NUE} \leq 0.90$ kg N kg^{-1} N), and fields with low NUE ($\text{NUE} < 0.50$ kg N kg^{-1} N) due to inefficient N use. The threshold of 80 kg N ha^{-1} for Ns proposed by the EUNEP is already considered very high for conditions in the Netherlands, as it incurs potentially high N losses to the environment (e.g., NO_3^--leaching, NH_3 and N_2O volatilization and denitrification). The target range for NUE and the Ns threshold represent the averages observed in Europe (Oenema et al., 2009) and were thus proposed by the panel for arable cropping systems (EUNEP, 2015). No specific target value was used for NEI, instead this indicator was simply compared across different crops.

The target range for NUE and the Ns threshold depend on biophysical conditions as well as on the type of agricultural system and N inputs used. Therefore, it is important to explore alternative target values based on the variation observed in the farmers' field data. Similar to Quemada et al. (2020), we explored the implications of adopting more modest and more ambitious targets for NUE and Ns for each crop. The median (Q2) observed NUE and Ns were considered as the 'modest' targets, while the third quantile (Q3) observed NUE value and first quantile (Q1) Ns value were considered as the 'ambitious' targets for the respective indicator. These target values were derived per crop and per soil type as averages over the study period.

2.2. Individual farmer field data

2.2.1. Database description

The data used in this study were self-recorded by farmers in commercial farm management systems for crop registration. The database covers the main agricultural regions and cultivated crops of the Netherlands during the period 2015–2017 ($n = 10{,}136$ crop field-year combinations; Fig. 1) and contains detailed information on biophysical conditions (e.g., daily weather information and soil type) and crop management (e.g., sowing and harvest dates, water and nutrient management) at field level. Further details about the data are provided in Silva et al. (2020), with the difference that potato and wheat fields without application of organic fertilisers were included in the present analysis. Descriptive statistics of nutrient management and N performance indicators per crop variety are provided as Supplementary Material (Tables A1 and A2).

This study focuses on the seven main arable crops cultivated in the Netherlands (Fig. 1). Potato is cultivated throughout the country with ware potatoes being produced for direct consumption and French fries, seed potatoes for small size and healthy seed tubers, and starch potatoes for the starch industry. Sugar beet is mainly produced for refined sugar, spring onions for direct consumption, winter wheat for livestock feed and spring barley for the malt and beer industry or feed. Crop yields were recorded by the farmers in t FM ha^{-1}. N management information was also recorded by the farmers and included the date of individual fertiliser applications, as well as the amount, fertiliser type and method used in each application (Table 1 and Fig. 2). Total N applied in a given field was estimated based on the amount and the N concentration of the

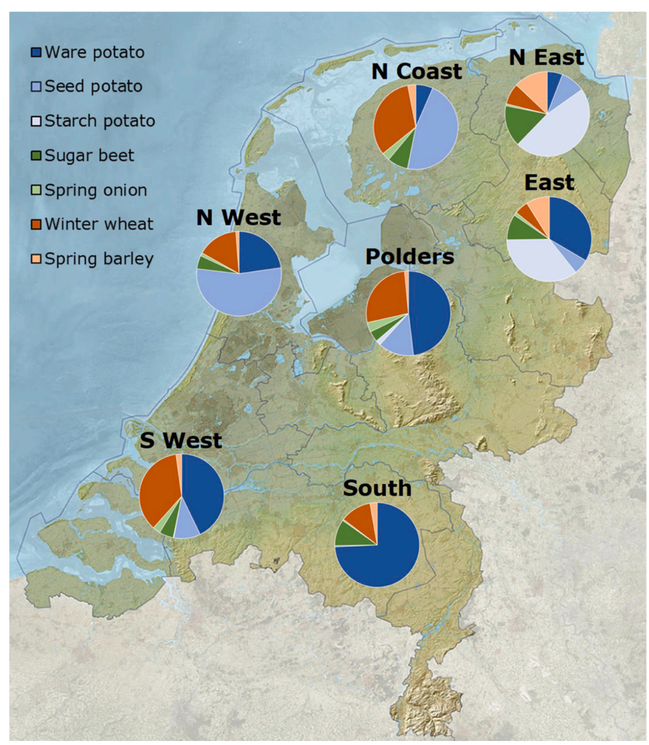

Fig. 1. Main agricultural regions in the Netherlands and share of crop field-year combinations per region. Total sample size per region was 583 field-year combinations in the East, 1177 field-year combinations in the N Coast, 1802 field-year combinations in the N East, 827 field-year combinations in the N West, 680 field-year combinations in the Polders (i.e., Flevoland), 3298 field-year combinations in the S West and 804 field-year combinations in the South. There were another 966 field-year combinations spread across other regions, which makes a total sample of 10,136 field-year combinations.

Table 1
Method used to apply N in the form of mineral fertiliser, slurry and manure for the main arable crops in the Netherlands. Note that plant available N applied differs from total N input, as the latter is not corrected with replacement values, and also includes N deposition.

	Ware potato	Seed potato	Starch potato	Sugar beet	Spring onion	Winter wheat	Spring barley
Mineral fertiliser							
N applied (kg N ha^{-1})	147.6	76.4	62.3	78.6	122.2	154.4	59.8
Placement (%)	2.3	12.2	1.6	0.4	0.1	0.3	0.3
Spreading (%)	97.3	86.8	95.7	99.4	99.9	99.5	98.5
Injection (%)	0.4	0.4	2.6	0.2	0.0	0.0	1.2
Other method (%)	0.0	0.5	0.1	0.0	0.0	0.1	0.0
Pig and cattle slurry							
N applied (kg N ha^{-1})	25.0	6.4	51.3	27.5	3.2	23.8	16.9
Placement (%)	0.3	0.0	0.0	0.0	0.0	0.4	0.0
Spreading (%)	1.7	6.1	0.4	0.0	2.9	1.4	0.0
Injection (%)	77.9	89.6	98.1	99.5	97.1	46.2	100.0
Other method (%)	20.2	4.3	1.5	0.5	0.0	52.0	0.0
Pig and cattle manure							
N applied (kg N ha^{-1})	10.2	2.3	22.2	13.3	1.4	8.4	5.8
Placement (%)	0.0	0.0	0.3	0.0	0.0	0.0	0.0
Spreading (%)	1.3	1.2	5.8	4.1	14.3	4.3	0.0
Injection (%)	92.6	93.8	91.9	92.5	85.7	68.3	100.0
Other method (%)	6.1	5.0	1.9	3.4	0.0	27.4	0.0

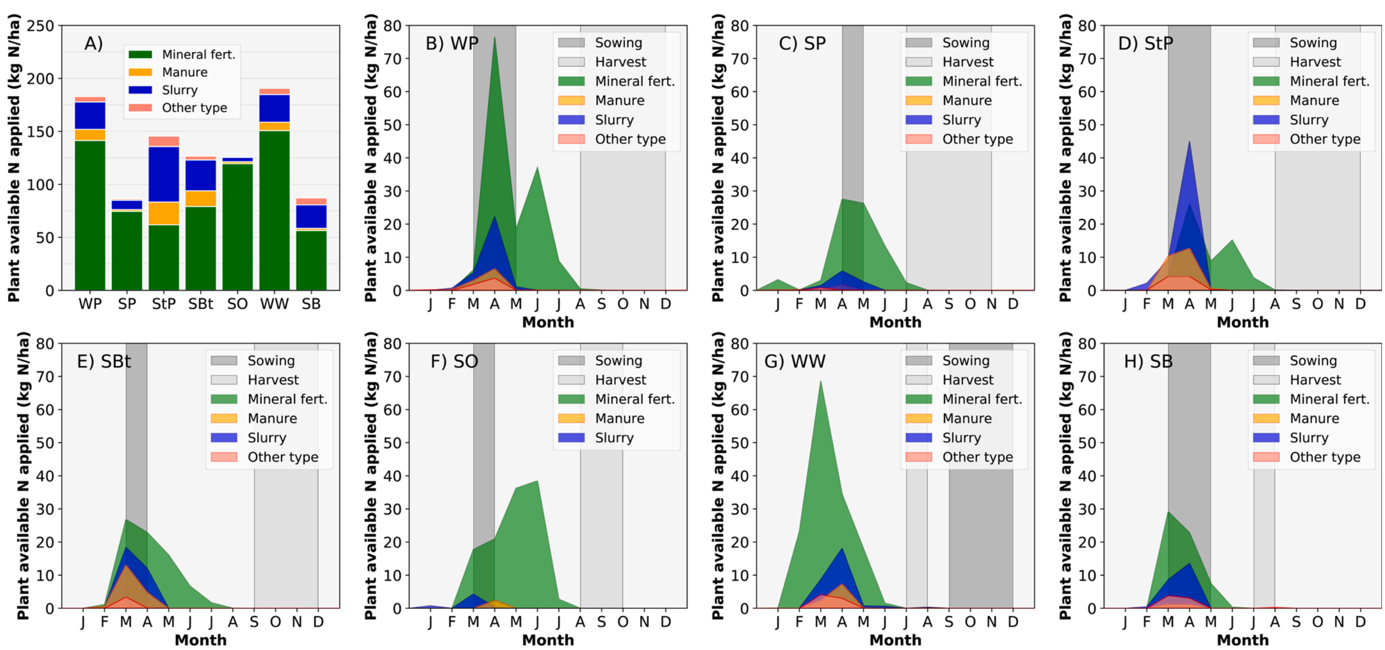

Fig. 2. N management of arable crops in the Netherlands: (A) mean plant available N applied from different sources during the period 2015–2017 and B–H) amount of plant available N applied by source and time in the year 2017 only. In (B–H) N application was calculated for each crop as the ratio between the plant available N applied across all farms with a given fertiliser type and in a given month and, the total crop area cultivated by all farms in 2017. Crop codes: WP = ware potato, SP = seed potato, StP = starch potato, SBt = sugar beet, SO = spring onion, WW = winter wheat, SB = spring barley.

different fertiliser types applied. N concentrations in mineral fertilisers were retrieved from labels of commercial products. For organic fertilisers, they were either self-reported by the farmer or else a default value per manure type was assumed (cf. Fig. A1). Fields with fertiliser applications reported after harvest time or in the year previous to the sowing of the crop were not considered in the analysis.

2.2.2. N management practices

Plant available N applied was estimated with Eq. (6) and it had an average value of ca. 185 kg N ha^{-1} for ware potato and winter wheat, 145 kg N ha^{-1} for starch potato, 125 kg N ha^{-1} for sugar beet and spring onion and less than 100 kg N ha^{-1} for seed potato and spring barley (Fig. 2A). Mineral fertilisers were the main source of N applied for all crops: from ca. 40% for starch potato up to more than 80% for spring onion and seed potato. Slurries were the second most used fertiliser type (between 5% for spring onion and 35% for starch potato), followed by solid manures (between close to nil for spring onion and seed potato, up to 15% for starch potato) and by other types of organic fertilisers (less than 10% for all crops). Most N was applied in the spring months around sowing or right after sowing of the tuber, root and bulb crops and spring cereals (Fig. 2B–H). This was true for slurry and manure which are applied before sowing (with the exception of winter wheat), while mineral fertilisers are also applied during the growing season. Organic fertilisers were incorporated in the soil through injection (mandatory) while mineral fertilisers were mostly applied through spreading (Table 1).

2.3. Understanding variability of NUE and Ns

2.3.1. Biophysical conditions

The effects of year and soil type on NUE and Ns were assessed for each crop with analysis of variance (ANOVA) using the general linear model procedure in R (Table A4). The interaction between year and soil type was also tested but it had no significant effect on NUE or Ns for any of the crops (data not shown). A post hoc Tukey test was further used to compare the NUE and Ns means across different years (2015–2017) and soil types (sand and clay). This was implemented with *HSD . test* function of the R package *agricolae* (de Mendiburu, 2015), only for the factors which had a statistically significant effect in the ANOVA.

2.3.2. Amount of N applied

The determinants of total N applied for each crop were investigated using multiple linear regression. This analysis considered total N applied as the dependent variable and the biophysical conditions (year, soil type and amount of spring and summer rainfall), variety type cultivated (see Silva et al., 2020), management conditions (e.g., N application moments and amount of spring and summer irrigation), field size and region (Flevoland, N Coast, N East, N West, East, South, S West; Fig. 1) as independent variables. The intercept and coefficients of the regression models were estimated for the pooled sample of each crop using ordinary least squares (OLS, *lm* function in R) with categorical variables expressed as dummies and continuous variables centered at the mean prior to the analysis. All variables included were uncorrelated (i.e., variable inflation factor smaller than 10) and no patterns were observed in the residual plots of the different models.

2.3.3. Source of N applied

For each crop × field × year combination, NUE and Ns were not only estimated based on total N applied, but also based on plant available N applied (corrected with fertiliser N replacement values; Eq. (6)). This was done because plant available N applied is relevant from a legislative and agronomic point of view when both mineral and organic fertilisers are used and result in different levels of NUE and Ns. To do so, plant available N applied was used instead of total N applied in the calculation of N inputs (Eq. (2)) and NUE and Ns were recalculated accordingly using Eqs. (3) and (4). NUE and Ns based on both total and plant available N applied were compared. Average NUE and Ns were also assessed for fields with only mineral fertilisers applied, with only organic fertilisers applied and with both mineral and organic fertilisers applied in a given soil type.

2.3.4. Time of N applied

The effect of N fertiliser application splits and N application date (in days after sowing, DAS) on NUE was analyzed for a subset of fields only. This subset included fields with N input in the range of average N input plus or minus 20 kg N ha^{-1} in order to remove confounding effects between amount of N applied and the number of split N dressings (Table 2). For this subset and for each crop, NUE was calculated for fields with one, two or three or more split N dressings, to allow for comparisons between these different groups. The effects of N application dates on NUE were assessed for yet another subset of the data focusing on the year 2017 (the most recent year) and clay soils and for ware potato, sugar beet and winter wheat only. This was done to control for biophysical differences between years and soil types that can mask the effects of split fertiliser applications and to focus the results on the crops with largest sample sizes.

2.3.5. Method of N applied

N application method was recorded by the farmers for each fertiliser application moment as placement, spreading, injection or other type. This makes it possible to compute the amount of N applied with a given method and from a given source (e.g., mineral fertiliser, manure or slurry) to each crop. Descriptive statistics of these data indicate a great confounding between the source of N applied and the method of application, meaning that a specific method was mostly used by farmers to apply a specific source of N (Table 1). For instance, 85% of the plant available N from mineral fertilisers was applied through broadcast application for all crops. Similarly, more than 90% of the plant available N applied with (pig and cattle) slurry to starch potato and sugar beet was injected in the soil. This ratio was slightly smaller for ware potato and, especially, winter wheat for which a considerable amount of N from slurry and manure was applied through other (unspecified) methods. The lack of variation in these data makes it difficult to isolate the effects of N method from the effects of N source on NUE and hence, the method of N application was not used in statistical analysis.

2.4. Performance at farm level and over time

Correspondence analysis was used to analyze (1) the performance of different crop types within a farm in a given year and, (2) the trends in NUE over time for a given crop in a given farm. The first makes explicit how NUE varies for different crops within single farms. This helps visualizing, for instance, the number of farms that can achieve high NUE for all crops or the number of farms that compromise the NUE in one crop to achieve higher NUE in another crop. The second helps analyzing the evolution of NUE for a given crop in a given farm, allowing to summarize consistency or changes in NUE over time. The results of the correspondence analyses were presented as alluvial diagrams developed using the R packages *ggplot2* and *ggalluvial* (Brunson, 2018; Wickham, 2016). Before doing so, the NUE observed in individual fields was averaged per farm, per crop type (i.e., potato, root and bulb and, cereal) and per year. For this specific analysis, NUE values above 0.75 kg N kg^{-1} N were classified as 'high', between 0.50 and 0.75 kg N kg^{-1} N as 'intermediate' and below 0.50 kg N kg^{-1} N as 'low'. Very efficient farms were identified as those with NUE above 0.75 kg N kg^{-1} N for each of the three different crop types. These were further screened for details on biophysical conditions and crop management practices.

The dataset did not allow for a proper analysis at cropping systems level as farmers did not report data for all the crops cultivated in their farms. Yet, we applied the EUNEP framework to a subset of farms for which data for two or more crops in a single year were available ($n = 329$ farm × year combinations), which is the closest approximation the dataset allows to an analysis at cropping systems or whole-farm level. For this purpose, the sum of N inputs and the sum of N outputs were calculated, respectively, across all crops per farm x year combination. NUE was then expressed as the ratio of the two sums, and Ns as their difference. The calculation over all (documented) crops per farm accounts, to a certain extent, for internal recycling through N mineralization, and for compensations between crops in the rotation.

Table 2

Determinants of total N applied in farmers' fields for the main arable crops in the Netherlands. The reference level of categorical variables is as follows: 'Region' = Flevoland, 'Year' = 2015, 'Soil' = Clay, 'Variety' = Early maturity for potatoes, not resistant against Rhizomania, Rhizoctonia or cyst nematodes for sugar beet, Red for onion, Bread baking for wheat and Feed for barley. Significance codes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

	Ware potato	Seed potato	Starch potato	Sugar beet	Spring onion	Winter wheat	Spring barley
Intercept	238.88***	94.87***	258.36***	100.41***	120.04***	225.59***	102.82***
Region_N Coast	−51.35***	5.76		28.99*	−20.49#	−25.73***	6.54
Region_N West	−52.58***	12.77		8.47	36.04*	−39.14***	25.72
Region_N East	−25.48*	31.41***	−36.54*	34.94**	−3.55	−64.62***	1.97
Region_East	−19.55*	17.91	−18.89	22.37	25.13	−33.38*	2.89
Region_S West	−17.78***	−1.51	−109.97**	25.42*	9.33	−13.95**	3.05
Region_South	−53.69***	−8.25		32.22*	−69.94**	−39.06***	6.45
Year_2016	17.42*	−10.82	13.02	6.86	−16.20	25.03***	1.94
Year_2017	0.67	−2.49	19.25**	17.12**	1.71	11.94***	−7.90
Soil_Sand	7.31	−10.03	−15.86*	29.65***	1.58	−14.28	9.96
Variety_Medium maturity	−12.31***	−3.81	92.18*				
Variety_Late maturity	−4.52	9.88	−27.96				
Variety_Rhizoctonia				−2.68			
Variety_Rhizomania				0.30			
Variety_CystNem				8.76			
Variety_Rhizomania &CystNem				9.33			
Variety_Yellow					11.26		
Variety_Other						2.02	
Variety_Malt							−5.07
Application moments (#)	14.83***	7.07***	24.25***	9.66***	14.45***	38.43***	8.26***
Field size (ha)	0.82	0.10	0.07	0.59	−0.63	0.00	0.21
Spring rainfall (mm)	−0.06***	−0.02	−0.03	−0.05	0.01	−0.13***	0.01
Summer rainfall (mm)	0.00	−0.09	0.08	−0.02	−0.24*	−0.02	0.08
Spring irrigation (mm)	0.27*						
Summer irrigation (mm)	0.00						
Adjusted-R^2	0.14	0.06	0.19	0.18	0.33	0.32	0.08
Sample size (*n*)	2611	815	734	570	160	1939	361

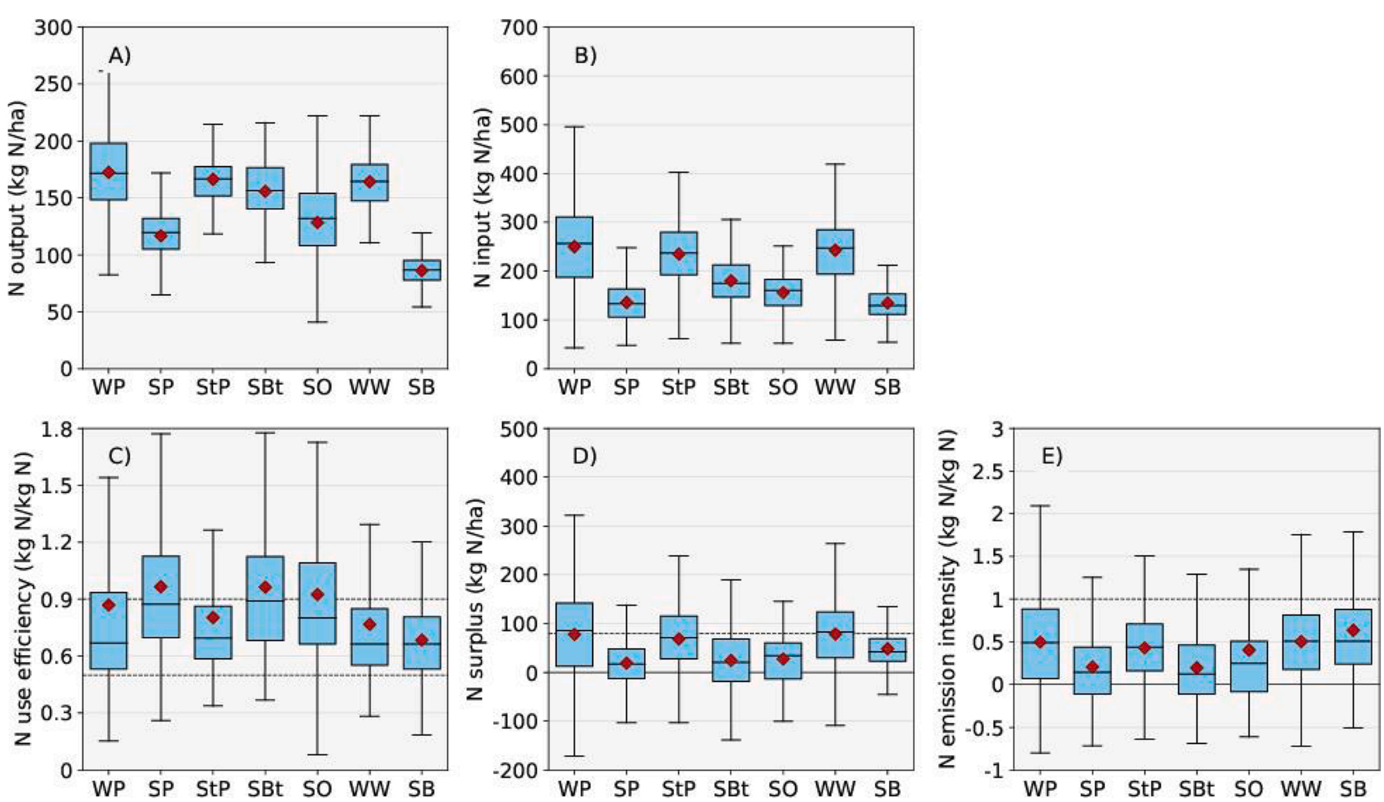

Fig. 3. N indicators for arable crops in the Netherlands: (A) N output, (B) N input, (C) N use efficiency, (D) N surplus and (E) N emission intensity. Data refer to the period 2015–2017. Dashed lines in (C) indicate NUE equal to 0.50 and 0.90 kg N kg^{-1} N and the dashed line in (D) indicates Ns equal to 80 kg N ha^{-1}. Diamonds indicate averages. Codes: WP = ware potato, SP = seed potato, StP = starch potato, SBt = sugar beet, SO = spring onion, WW = winter wheat, SB = spring barley.

3. Results

3.1. N indicators for arable crops in the Netherlands

3.1.1. N output and N input

The variation in N output and N input for the different crops is provided in Figs 3A and B. N output was greatest for ware and starch potato (172 and 166 kg N ha^{-1}, respectively) followed by winter wheat (164 kg N ha^{-1}), sugar beet (155 kg N ha^{-1}), spring onion (128 kg N ha^{-1}), seed potato (116 kg N ha^{-1}) and spring barley (86 kg N ha^{-1}). There were also differences in the variation of N output for different crops. For instance, the standard deviation of N output was greatest for spring onion (ca. 35 kg N ha^{-1}) and ware potato (ca. 30 kg N ha^{-1}) while for sugar beet and seed potato it was ca. 25 kg N ha^{-1}. The lowest variation in N output was observed for winter wheat and starch potato (ca. 20 kg N ha^{-1}) and for spring barley (ca. 15 kg N ha^{-1}). We note that cereals and sugar beet are usually directly weighted and delivered while potato and onion are usually stored on farm. For the latter crops, farmers make an estimation of yield while harvesting and this likely results in greater inaccuracy in the estimated crop yield and corresponding N output. N input was greatest for ware potato (250 ± 95 kg N ha^{-1}), winter wheat (245 ± 75 kg N ha^{-1}) and starch potato (235 ± 70 kg N ha^{-1}), intermediate for sugar beet and spring onion (180 ± 55 and 155 ± 45 kg N ha^{-1}, respectively) and lowest for seed potato and spring barley (135 ± 45 and 135 ± 35 kg N ha^{-1}, respectively).

3.1.2. N-use efficiency (NUE)

The average NUE was within the EUNEP target range of 0.50–0.90 kg N kg^{-1} N for all crops except seed potato, sugar beet and spring onion for which values around 0.95 kg N kg^{-1} N were observed (Fig. 3C). Average NUE of ware potato was also rather high (ca. 0.87 kg N kg^{-1} N), followed by starch potato and winter wheat (ca. 0.80 kg N kg^{-1} N) and spring barley (ca. 0.70 kg N kg^{-1} N). The average NUE was greater than the median NUE for most crops (Fig. 3C). Median NUE was between 0.5 and 0.9 kg N kg^{-1} N for all crops: 0.67 kg N kg^{-1} N for ware potato, 0.87 kg N kg^{-1} N for seed potato, 0.70 kg N kg^{-1} N for starch potato, 0.89 kg N kg^{-1} N for sugar beet, 0.80 kg N kg^{-1} N for spring onion and 0.66 kg N kg^{-1} N for winter wheat and spring barley.

NUE above 0.90 kg N kg^{-1} N was observed in ca. 50% of the sugar beet fields, 45% of seed potato fields, 40% of spring onion fields, 25% of ware potato fields, ca. 20% of starch potato and winter wheat fields and less than 15% of spring barley fields (Fig. 3C). The large number of sugar beet, seed potato and spring onion fields with NUE above 0.90 kg N kg^{-1} N reflects farmers' strategies to avoid economic yield or quality losses, which may be expected to occur for these crops if too much N is applied. NUE was smaller than 0.50 kg N kg^{-1} N for ca. 20% of ware potato and spring barley fields, 15% for winter wheat fields and less 10% of the fields of the other crops (Fig. 3C). This means that NUE was within the EUNEP target range of 0.50–0.90 kg N kg^{-1} N for 45–55% of the ware potato, seed potato, sugar beet and spring onion fields, and for 65-70% of the starch potato, winter wheat and spring barley fields.

3.1.3. N surplus (Ns)

Ns was on average below the threshold value of 80 kg N ha^{-1} for all crops (Fig. 3D). Ns was greatest for winter wheat and ware potato (78 kg N ha^{-1}), followed by starch potato (68 kg N ha^{-1}), spring barley (48 kg N ha^{-1}), sugar beet and spring onion (ca. 25 kg N ha^{-1}) and seed potato (less than 20 kg N ha^{-1}). There was a negative relationship between NUE and Ns, as crops with greatest NUE exhibited the smallest Ns (Fig. 3C and D; see also Fig. A6). There was also a positive relationship between Ns and N input (Figs. 3B, D and A2). Despite the overall negative relation between NUE and Ns, the relatively high NUE found in most crops (Fig. 3C) did not ensure low Ns for all fields. N inputs can likely be reduced in many fields with little or no reduction in N output (Figure A2). Ns above 80 kg N ha^{-1} was observed for ca. 50% of the ware potato and winter wheat fields and ca. 40% of starch potato fields (Figure A2D). The proportion of fields with Ns above this threshold was between 10% and 20% for the other crops.

3.1.4. N emission intensity (NEI)

The NEI was on average ca. 0.65 kg N kg^{-1} N for spring barley and smaller for the other crops (Fig. 3E). Average NEI was 0.5 kg N kg^{-1} N for ware potato and winter wheat, ca. 0.40 kg N kg^{-1} N for starch potato and spring onion and, 0.20 kg N kg^{-1} N for seed potato and sugar beet. In other words, N output is on average considerably greater than Ns for most crops but we also note there was a lot of variation in NEI across fields for all crops (Fig. 3E). For instance, Ns was greater than N output (i.e., NEI ≥ 1) for ca. 20% of ware potato and spring barley fields, 15% of winter wheat fields, 10% of starch potato and spring onion fields and 5% of seed potato and sugar beet fields.

3.2. Biophysical and management determinants of NUE and Ns

3.2.1. Differences across years and soil types

There was a significant effect of year on NUE for ware potato, sugar beet and winter wheat (Fig. 4A). NUE was lowest in 2016 for these crops, which was also the year with the lowest yields (data not shown). There were no significant differences in NUE between 2015 and 2017 for all crops except winter wheat, for which NUE was greatest in 2015. The difference between the crop × year specific NUE was 0.20 kg N kg^{-1} N for winter wheat and at most 0.10 kg N kg^{-1} N for the other crops. There were also significant year effects on Ns for ware potato, starch potato and winter wheat (Fig. 4B). Year effects on Ns were fairly similar for ware and starch potato and years with highest NUE had the lowest Ns and vice-versa. The difference between year-specific Ns was ca. 40 kg N ha^{-1} for winter wheat, ca. 30 kg N ha^{-1} for ware and starch potato, ca. 20 kg N ha^{-1} for spring onion and less than 10 kg N ha^{-1} for the other crops.

The effect of soil type on NUE was significant for ware potato, seed potato, sugar beet and spring barley (Fig. 4C). NUE was greater in sandy than in clay soils for ware potato (0.92 vs. 0.85 kg N kg^{-1} N), while the opposite was true for seed potato (0.98 vs. 0.83 kg N kg^{-1} N), sugar beet (1.07 vs. 0.81 kg N kg^{-1} N) and spring barley (0.74 vs. 0.65 kg N kg^{-1} N). Regarding Ns, there was a significant effect of soil type for ware, seed and starch potato, sugar beet and spring barley (Fig. 4D). Ns was greater in clay than in sandy soils for ware potato (85 vs. 60 kg N ha^{-1}) and starch potato (95 vs. 60 kg N ha^{-1}), while the opposite was true for seed potato (40 vs. 15 kg N ha^{-1}), sugar beet (60 vs. nil kg N ha^{-1}) and spring barley (55 vs. 40 kg N ha^{-1}). Differences in NUE and Ns between years and soil types were mainly associated with differences in yields, not in N application levels (Table A6).

3.2.2. N application rates

Plant available N applied ranged between minimum values of less than 25 kg N ha^{-1} (most crops) up to a maximum of ca. 350 kg N ha^{-1} for ware potato, starch potato and winter wheat, ca. 200 kg N ha^{-1} for seed potato, sugar beet and spring onion and ca. 150 kg N ha^{-1} for spring barley (data not shown). Rates of plant available N applied in clay soils were above the recommendation (see Table A3) for ca. 90% of the malt barley fields, 50% of the feed barley fields, 30% of the ware and starch potato fields, 25% for the sugar beet fields, and for winter wheat fields with varieties for other purposes than baking, and for 15–20% of the seed potato fields, spring onion and baking wheat fields (Fig. A3). The proportion of fields above the N recommendation was much smaller in sandy soils (Fig. A3 and Table A3), which is consistent with stricter formal application standards there. For each crop, fields with reported plant available N applied above the N recommendation exhibited on average greater plant available N applied than fields with plant available applied below the N recommendation (Fig. A4) yet, no major yield differences were observed between fields with plant available N applied

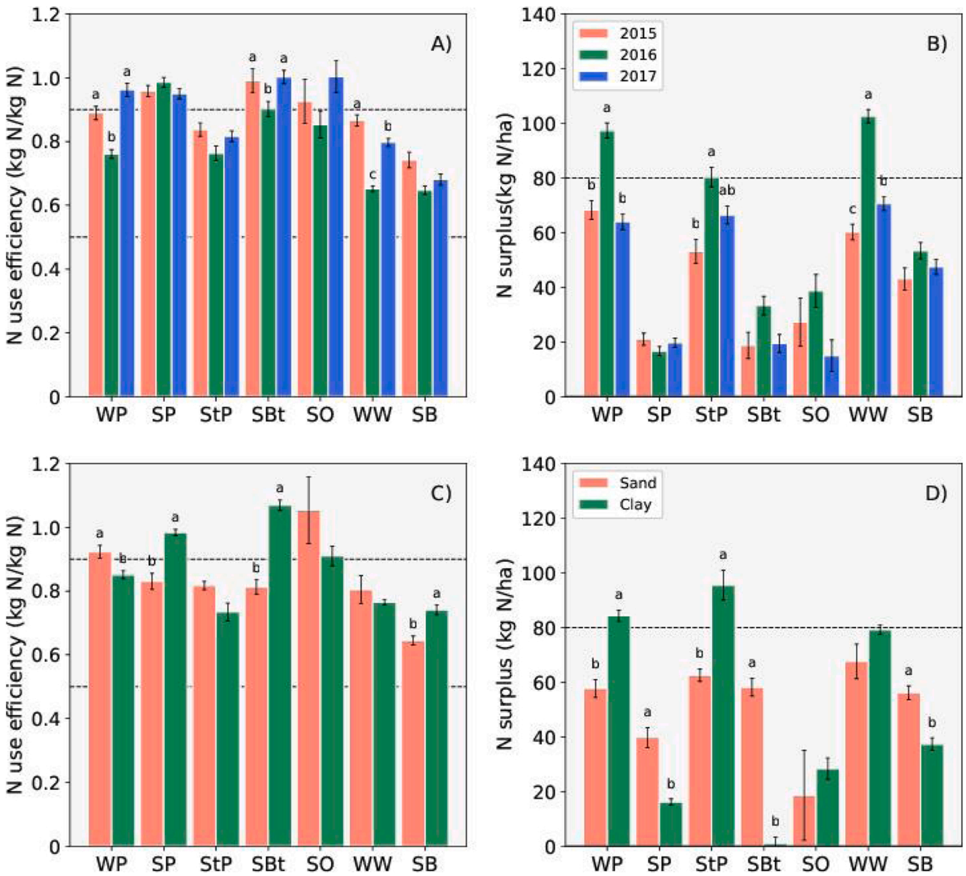

Fig. 4. N use efficiency (NUE) and N surplus (Ns) of arable crops in the Netherlands per year (A, B) and soil type (C, D). Error bars show standard errors of the mean and dashed lines show the NUE target and Ns threshold values proposed by EUNEP (2015). Lower case letters indicate significant differences between years or soil types per crop ($p \leq 0.05$). Codes: WP = ware potato, SP = seed potato, StP = starch potato, SBt = sugar beet, SO = spring onion, WW = winter wheat, SB = spring barley.

below and above the N recommendation (Fig. A5).

The determinants of total N applied, the main component of N input, were studied to understand what characterizes fields with low N input and high NUE (Table 2). For ware potato and winter wheat, significantly greater amounts of N were applied in Flevoland compared to other regions. The lowest N application rates were observed in the South, N West and N Coast for ware potato, in Flevoland for seed potato and in the N East for starch potato. Compared to Flevoland, total N applied was significantly greater in the N Coast, N East, S West and South for sugar beet and, significantly greater in N West and lower in the South for spring onion. Finally, there were no significant differences in total N applied across regions for spring barley.

Total N applied was significantly greater in sandy than in clay soils for sugar beet, while the opposite was true for starch potato (Table 2). Significant differences in total N applied across different years were observed for ware potato, starch potato, sugar beet and winter wheat, but the effects were generally small (ca. 20 kg N ha^{-1}). In general, there were no clear differences in total N applied across variety types for most crops. There was no association between spring rainfall and total N applied for all crops except ware potato and winter wheat for which a significant negative relationship between both was observed. A negative relationship between total N applied and summer rainfall was also observed for spring onion. For ware potato, greater amounts of irrigation water in spring were associated with greater total N applied while there was no association between total N applied and summer irrigation. No significant association between total N applied and field size was found for either crop, but a very strong positive association between total N applied and the number of N application moments was observed for all crops (see also Fig. 6A).

The coefficient of determination (adjusted-R^2) of the fitted multiple linear regressions was above 30% for spring onion and winter wheat, ca. 20% for starch potato and sugar beet and less than 15% for ware potato, seed potato and spring barley. Other relevant factors not included in the analysis are the proximity to and cooperation with livestock farms or the financial risk associated with lower N application rates. The adjusted-R^2 of the fitted regressions are low and of similar magnitude as those found in other analyses of 'big data' in the Netherlands (Silva et al., 2021) and elsewhere (Assefa et al., 2020; Silva et al., 2020).

3.2.3. N source and fertiliser type

Plant available N input was 75% of total N input for starch potato, 85–90% for sugar beet and spring barley, and more than 90% for ware potato, seed potato, spring onion and winter wheat (data not shown). As expected, replacing total N applied with plant available N applied resulted in greater NUE and lower Ns, and the magnitude of this difference was determined by the share of organic fertiliser applied to the respective crops (Fig. 5A and B). Differences in NUE estimated with plant available N or with total N were as high as 0.30 kg N kg^{-1} N for starch potato and less than 0.15 kg N kg^{-1} N for the other crops. Differences in Ns based on plant available N and total N were ca. 55 kg N ha^{-1} for starch potato, ca. 30 kg N ha^{-1} for ware potato and sugar beet, ca. 20 kg N ha^{-1} for cereals and less than 10 kg N ha^{-1} for seed potato and spring onion.

NUE was smallest and Ns largest for fields which received both mineral and organic fertilisers and NUE was greatest for fields which received only mineral fertiliser (Fig. 5C). This was particularly true for tuber, root and bulb crops in sandy soils and for seed potato and sugar beet in clay soils. Ware potato, starch potato and winter wheat receiving either exclusively mineral fertiliser or organic fertiliser exhibited a similar NUE in clay soils. The effect of fertiliser type on Ns was opposite to that on NUE: the greatest Ns was observed in fields with both mineral and organic fertilisers applied and the smallest Ns in fields with only mineral fertiliser (Fig. 5D). This was true for clay and sandy soils, with exceptions per crop as described for NUE. Mineral fertilisers are effective

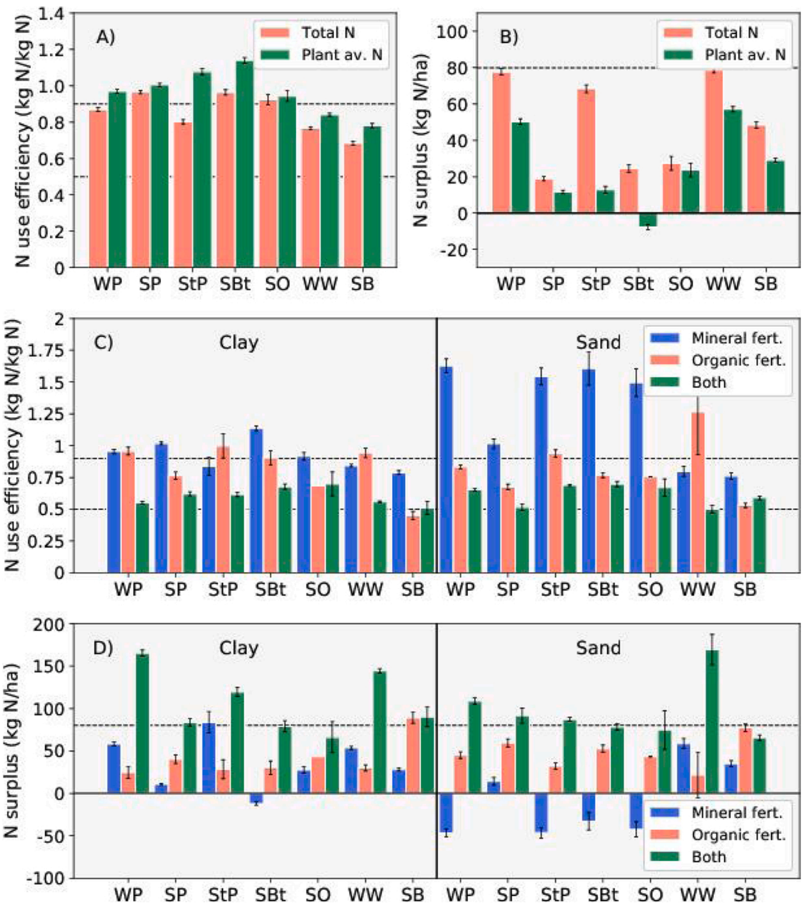

Fig. 5. Effect of fertiliser type on (A) N use efficiency and (B) N surplus; and performance of fields with only mineral fertiliser, only organic fertiliser or both mineral and organic fertilisers regarding (C) N use efficiency and (D) N surplus for arable crops in the Netherlands. N use efficiency and N surplus are expressed based on total N inputs in panels (C) and (D). 'Plant av. N' stands for plant available N applied (Eq. (6)). Codes: WP = ware potato, SP = seed potato, StP = starch potato, SBt = sugar beet, SO = spring onion, WW = winter wheat, SB = spring barley.

and efficient in the year of application and can be applied during the growing season when crop N uptake rates are highest, hence resulting in high NUE and low Ns. Conversely, organic fertilisers are effective over multiple years (i.e., not all N in organic form is available for crop uptake in the application year) and the availability of N from these sources is difficult to control which explains a low NUE and relatively high Ns.

3.2.4. N time and application moments

There was no clear effect of the number of N application moments on NUE for most crops, when focusing on fields with relatively similar N application rates (Fig. 6A). However, when comparing all fields in the database, there was a negative relationship between NUE and the number N application moments for all crops due to the positive association between the latter and total N applied and the small marginal yield responses to applied N for most crops (Table 2 and Fig. A2, respectively). The only crop for which there were small increases in average NUE with increased number of N application moments at similar N input was seed potato: 0.82 kg N kg^{-1} N for fields with one N application moment, 0.87 kg N kg^{-1} N for fields with two N application moments and 0.89 kg N kg^{-1} N for fields with three or more N application moments (Fig. 6A). The aforementioned NUEs are comparable to the median NUE for the same subset of data (Fig. 6A).

The effect of N application date on NUE was rather unclear as NUE was highly variable for a given application date independently of the crop and the number of application moments (Fig. 6B–J). For ware potato and sugar beet with one N application moment, NUE was highest when N was applied around sowing (Fig. 6B and E). The same was true for the first N application moment in ware potato and sugar beet with two N application moments (Fig. 6C and F). However, NUE tended to increase with the second N application done at later dates for ware potato while the opposite was true for sugar beet. The highest NUE for ware potato with three N application moments occurred when the first and second application were done slightly before and after sowing, respectively, and the third application was done 50–70 DAS (Fig. 6D). For winter wheat, the highest NUE was observed for N application dates after 150 DAS up to ca. 200 DAS independently of the number of N application moments (Fig. 6H–J).

3.3. Farm performance for different crops and over time

There were 206 farms in the entire database that recorded crop yield and N management information for a given crop in 2015, 2016 *and* 2017. Out of these, 48 farms recorded data for two different crops and 3 farms recorded data for 4 different crops in a given year, meaning most data refer to single farm × crop × year combinations. The data allowed assessing changes in NUE over time for 279 unique farm × crop combinations (Fig. 7A). Out of these 279 observations, 116 exhibited a consistent performance over the three years: 60 had an NUE greater than 0.75 kg N kg^{-1} N, 3 had an NUE lower than 0.50 kg N kg^{-1} N and, 53 had an NUE between 0.50 and 0.75 kg N kg^{-1} N. Out of the 60 best performing farm × crop combinations, 36 referred to potato crops (15 for ware potato, 14 for seed potato and 7 for starch potato), 10 to winter wheat, 12 to sugar beet, 1 to spring onion and 1 to spring barley. Crop yields for these farms were generally high compared to the overall sample and plant available N applied with organic fertilisers comprised ca. 20% of total plant available N applied for ware potato and winter wheat, ca. 60% for starch potato and (close to) nil for seed potato, sugar beet, spring onion and spring barley (Table A6).

There were 129 farm × year combinations which recorded crop yield and N management data for three different crop types (i.e., potato, cereals and other crops; Fig. 7B). This subset of observations made it possible to assess compensatory effects of NUE across different crop

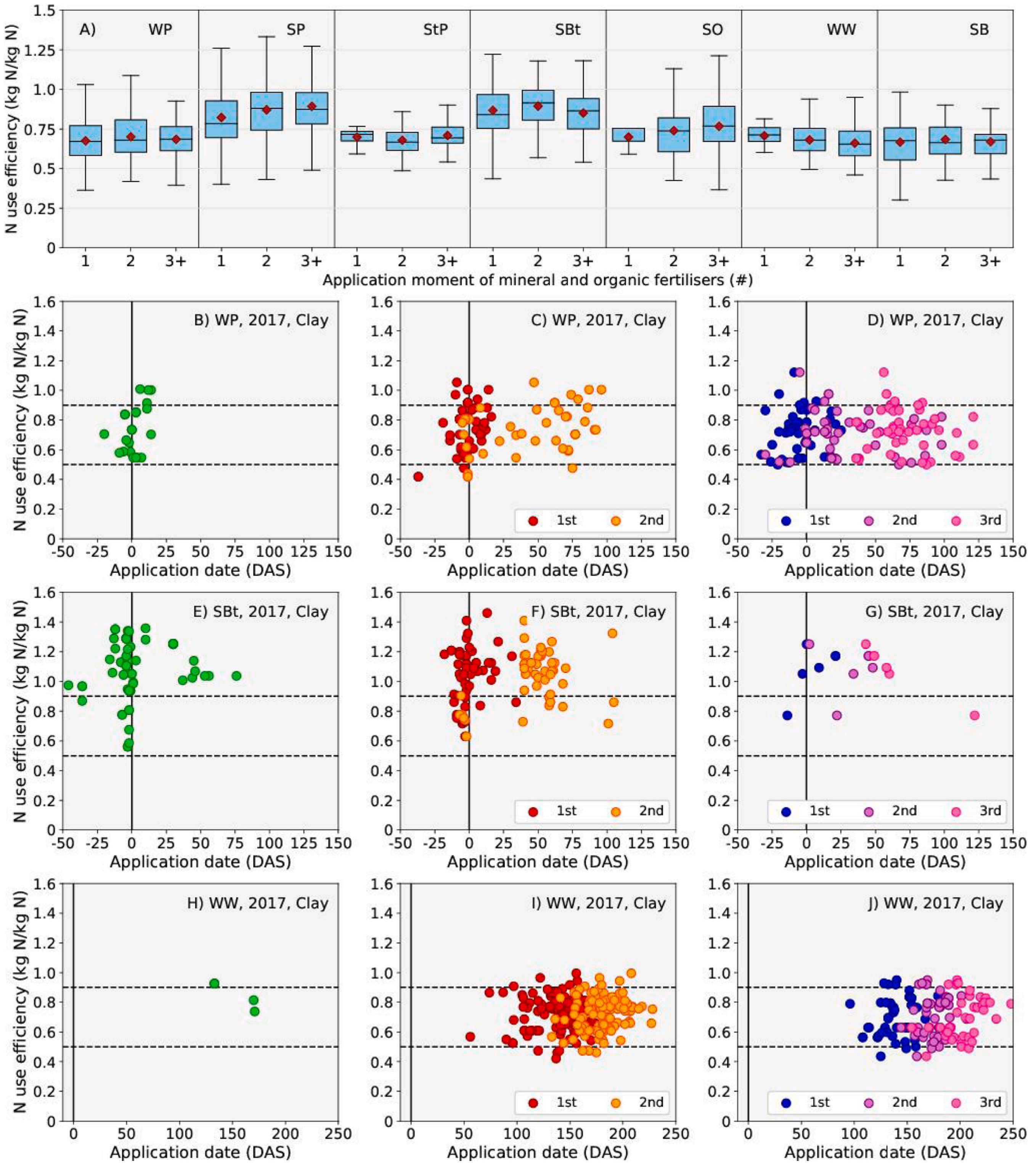

Fig. 6. Panel (A) N use efficiency in relation to the number of mineral and organic fertiliser application moments for fields with N input between mean N input plus/minus 20 kg N ha^{-1} during the period 2015–2017 and both clay and sandy soils. Panels (B–J) N use efficiency in relation to fertiliser application dates for ware potato (B–D), sugar beet (E–G) and winter wheat (H–J) fields with N input between mean N input plus/minus 20 kg N ha^{-1} but only in clay soils and the year 2017. Panels on the left, center and right show fields with one, two and three fertiliser applications, respectively. Fertiliser application dates are expressed in days before or after sowing (vertical solid line). Horizontal dashed lines show N use efficiency of 0.50 and 0.90 kg N kg^{-1} N.

types at the farm level. There was no farm × year combination with NUE lower than 0.50 kg N kg^{-1} N for all crop types, while 17 farm × year combinations achieved an NUE greater than 0.75 kg N kg^{-1} N for all crop types and 12 farm × year combinations had an NUE between 0.50 and 0.75 kg N kg^{-1} N for all crop types. The other farm × year combinations included in this subset of the data exhibited combinations of high, mid and low NUE for the different crop types as shown in Fig. 7B. Out of the 17 farm × year combinations with high NUE, 8 referred to the year 2017, 5 to the year 2015 and 4 to the year 2016 (Table A8). All these farms reported one cereal crop and two to four

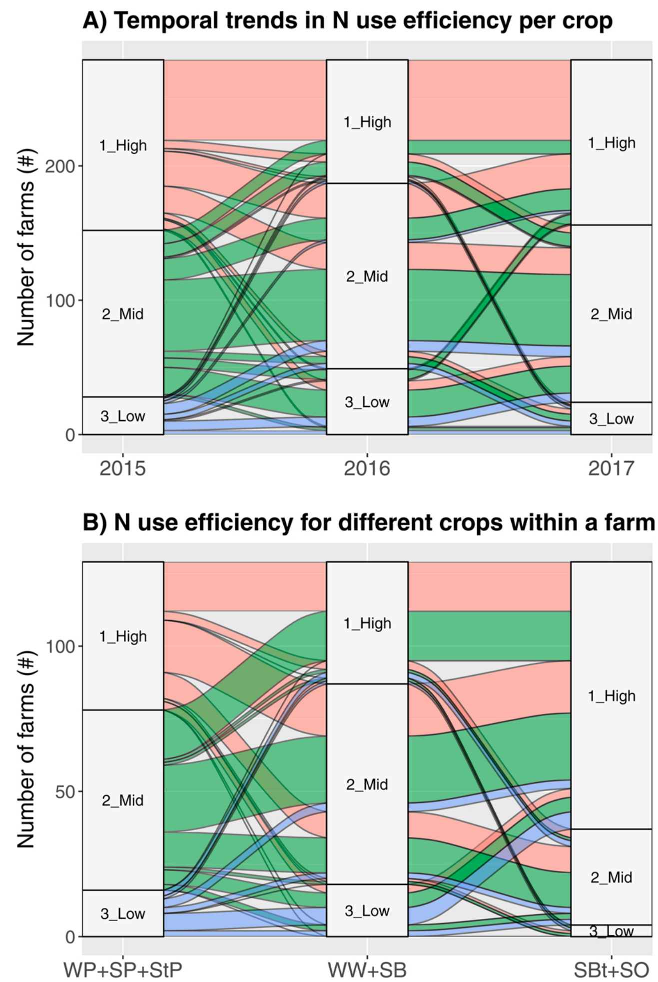

Fig. 7. Alluvial diagrams illustrating (A) the change in N use efficiency (NUE) for a given farm × crop in different years and (B) the NUE obtained for different crop types in given farm × year combinations. The height of a block in (A) represents the number of farms cultivating the same crop in different years and in (B) the number of farms cultivating at least one crop of each crop type in a given year. The thickness of each stream flow represents the size of the sample contained in both clusters connected by a given stream flow. The reader is referred to the main text for further explanation of the figure. Codes: '1_High': NUE $\geq$ 0.75 kg N kg^{-1} N; '2_Mid': 0.50 < NUE < 0.75 kg N kg^{-1} N; '3_Low': NUE $\leq$ 0.50 kg N kg^{-1} N.

tuber, root or bulb crops in a given year and had generally high crop yields when compared to the overall sample (Table A8). These farms shared similarities regarding N management of the different crops: plant available N applied for most crops in these farms was below the mean of the overall sample and, most crops were fertilised exclusively with mineral fertilisers except winter wheat for which a considerably amount of N was supplied with organic fertilisers (Table A8).

The EUNEP framework was applied to a subset of farm × year combinations for which N input and N output data were available for multiple crops (n = 329 farm × year combinations; Fig. 8). NUE and Ns for this subset were on average 0.69 kg N kg^{-1} N and 64 kg N ha^{-1}. NUE was within the EUNEP target range of 0.50–0.90 kg N kg^{-1} N for 243 out of 329 farm × year combinations (74% of the sample; Fig. 8A). Yet, Ns was above 80 kg N ha^{-1} for 157 out of 329 farm × year combinations (48% of the sample, Fig. 8A). An Ns above 80 kg N ha^{-1} was mostly observed for farm × year combinations with cereals and ware potato and not as much for farm × year combinations with cereals and other root, tuber or bulb crops (Fig. 8A). A negative relationship was found between N input for cereals and N input on other crops in farm × year combinations with the respective crop types (Fig. 8B). This negative relationship confirms that high levels of N input to one crop are to some extent compensated for by lower N input on other crops, to respect a formal farm-level input limit imposed by the (aggegated) crop level application standards. In general, results confirm the findings at crop level (Fig. 3): NUE for arable farms in the Netherlands is high and within the EUNEP target range, but Ns is also high for a substantial fraction of the farm × year combinations. As high NUE does not guarantee a low Ns, reducing N inputs is the most effective way to reduce Ns.

4. Discussion

4.1. N performance of Dutch arable crops

This study assessed the NUE and Ns of arable crops on farms in the Netherlands using a large database of farmer field data across three years. Average and median NUE were within the EUNEP target range of 0.50–0.90 kg N kg^{-1} N for most crops (Fig. 3C). While average Ns were below the threshold of 80 kg N ha^{-1} for all crops (Fig. 3D), about 40% of the ware potato, starch potato and winter wheat fields exhibited Ns above this target value. These results confirm the hypothesis that crop yields and NUE are high, but that Ns is also high, for arable crops in the Netherlands (Figs. 3 and A2) and that Ns can be high in spite of high NUE when N inputs are high (Fig. 3; Silva et al., 2020). There were also no yield differences, on average, between fields with plant available N applied below and above the N recommendation (Figs. A4 and A5), which supports our second hypothesis.

NUEs presented in this study were much greater than shown in earlier global NUE assessment for the Netherlands (Zhang et al., 2015;

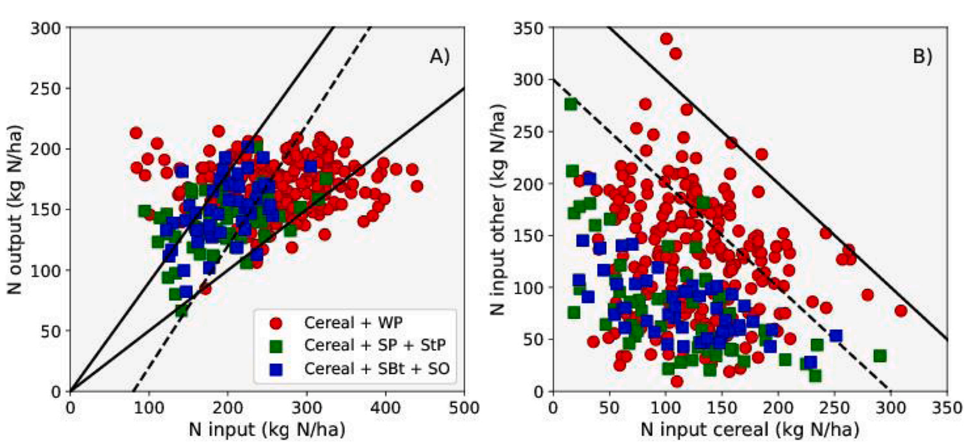

Fig. 8. N use efficiency (NUE) analysis for multiple crops within a farm: (A) NUE indicator of the EU N Expert Panel for farm x year combinations cultivating cereals and ware potato (WP), cereals, seed (SP) and starch potato (StP) and, cereals, sugar beet (SBt) and spring onion (SO) and (B) N input for cereals vis-à-vis N input for root, tuber and bulb crops for the same farm x year combinations shown in (A). Solid lines in (A) mark the target range for NUE of 0.50–0.90 kg N kg^{-1} N and the dashed line marks the Ns threshold value of 80 kg N ha^{-1}, all defined by the EU N Expert Panel. The solid and dashed line in (B) shows a N input of 400 and 300 kg N ha^{-1}, respectively.

Lassaletta et al., 2014). Global level studies use national statistics on fertilizer use and manure production, and assume that all manure produced is applied nationally. National reporting for the Netherlands indeed shows lower N inputs than global studies, but higher than the current crop and farm level study (CBS et al., 2020). Another key difference is that the average NUE reported here was estimated as an 'average of ratios' for hundreds of fields while global studies normally report average NUE as a 'ratio of averages' between N output and N input at national scale. This has large implications for the results: NUE of ware potato was 0.69 kg N kg^{-1} N when estimated as a 'ratio of averages' and 0.87 kg N kg^{-1} N when estimated as an 'average of ratios' as was done here (Fig. 3C).

The analysis of the biophysical and management determinants of NUE did not allow to identify clear and consistent strategies that can improve the performance of the cropping systems studied. To a large extent, and as discussed in Section 4.3, this may be a limitation of 'big data'. In addition, farmers' decisions on N management are taken ahead of the growing season with large uncertainties about crop growth conditions. As such, under-fertilization in a favorable year will not maximize crop yields while over-fertilization in a dry year will result in a high Ns as a result of yield losses due to drought. This probably explains the differences in NUE and Ns observed for some crops between years (Fig. 4): NUE was lowest in 2016 due to lower yields in this year (Silva et al., 2020) while the amounts of N applied were similar across years (Table 2). Conversely, consistent NUE differences were neither observed for the different crops in clay and sandy soils (Fig. 4) nor for fields with different N application dates and methods (Fig. 6 and Table 1).

The source of N applied had an important effect on NUE and Ns (Figs. 2 and 5). Organic manures and slurries are widely available in the Netherlands due to an intensive and large livestock sector. Arable farmers have agronomic and economic incentives to use organic fertilisers because these are cheaper than mineral fertilisers and also bring organic matter. Organic fertilisers are also an effective means to meet the requirements of phosphorus, potassium and other nutrients at crop rotation level, besides N. Although from a circularity perspective at regional level it is recommended to prioritize organic over mineral fertilisers, such prioritization is likely to negatively affect NUE at field level, at least in the short-term because part of N in organic fertilisers is not readily available and part is lost as ammonia. Finally, the high variability in nutrient compositions of organic manures makes it also difficult to match N availability, N demand and product quality (Fig. A1). This is why organic fertilisers are hardly used by farmers for seed potato, spring onion and spring barley where excessive N supply negatively affects crop yield or product quality (Fig. 2A).

When based on plant available N applied, NUE was higher and Ns lower for fields using only organic fertilizer than those using only mineral fertilizer (see Fig. A7). From the perspective of Dutch regulations, using organic fertilizers is more efficient for farmers because standard N fertilizer replacement values are considered and the extra N not accounted for in the year of application will become available in later years. As long as there is a large livestock sector, applying organic fertilizers on arable fields is efficient at regional or national level. However, our study shows that at field level total N inputs are often not adjusted by taking into account organic fertilizer applications in previous years (Fig. A2) or even in the current year (Fig. 5). Processing manure to products with better known and constant quality – the current policy direction – will allow for more judicious application in time and may contribute to more efficient use of organic fertilisers (e.g., Huygens et al., 2019). IT added precision farming to support decisions of N management during the growing season (Mulders et al., 2021) could then be a solution for both mineral and organic fertilisers.

NUE assessments at farm level and across multiple years are important to account for the long-term effects of organic manures on soil fertility, nutrient delivery and Ns (Schröder et al., 2003). Moreover, N application standards in the Netherlands are monitored and enforced at the farm level rather than at crop level, which allows farmers to shift part of the N budget between crops on the farm (Silva et al., 2017). For instance, sugar beet quality and sugar price are negatively affected by excess N while for ware potato trade-offs between fertiliser use and product quality are less evident. Our results indicate that only few farms reported consistent high or low NUE across the three years or for different crops within a year (Fig. 7); and that NUE and Ns for multiple crops within a farm were on average 0.69 kg N kg^{-1} N and 64 kg N ha^{-1}. This average NUE is slightly lower than the average NUE of 0.63 kg N kg^{-1} N reported by Silva (2017) for the year 2012 using a different dataset. In contrast, the average Ns reported in this study is considerably lower than that reported by Silva (2017) which was on average 93 kg N ha^{-1}. This difference might be attributed to misreported N applications or to the omission of other crops (e.g., grass, silage maize and vegetable crops) in the 'cropping systems' analysis presented here.

4.2. Safe operating space for crop production

Defining a safe operating space for N performance comprises different steps. Firstly, the relevant indicators and target values need to be defined as done by the EUNEP for the NUE and Ns based on averages observed across the EU (EUNEP, 2015). Secondly, target values need to be refined so that these are relevant and feasible at local level. The analysis of the distribution of NUE and Ns for a large number of farmers' fields can be used to derive more or less ambitious target values adapted to local conditions, as proposed and done by the EUNEP (cf. Quemada et al., 2020). The third step to define an operating space entails the comparison of the locally adapted target values to environmental limits (de Vries and Schulte-Uebbing, 2019) and economic requirements. The latter could replace the first step as a way to derive target values that could then be compared in a second step against what is achievable in practice.

The EUNEP (2015) framework defines a 'characteristic operating space' based on 0.50 and 0.90 kg N kg^{-1} N target values for NUE and the 80 kg N ha^{-1} threshold for Ns (Fig. A2). NUE values outside this range indicate inefficient N management (below 0.50 kg N kg^{-1} N) or N mining in the long-run (above 0.90 kg N kg^{-1} N), while Ns values above 80 kg N ha^{-1} are likely associated with environmental problems (e.g., nitrate leaching). However, applicability and validity of these target values still need further underpinning (Quemada et al., 2020). Below, the EUNEP target values were compared to those estimated based on the variability observed in the farmer field data analyzed here.

Two target values for NUE were derived per crop and soil type (average over 3-years) from the data, namely a 'modest' target based on the median (Q2) NUE and an 'ambitious' target based on the Q3 NUE values. The median NUE was above 0.60 kg N kg^{-1} N for all crop × soil type combinations, while the Q3 NUE value was above 0.90 kg N kg^{-1} N for potato crops in both soil types, for sugar beet in clay soils and for spring onion in sandy soils (Table 3). Q3 NUE for cereals was between 0.75 and 0.85 kg N kg^{-1} N. Adopting the median and Q3 NUE value rather than the target values proposed by EUNEP (2015) reduced the number of fields with intermediate NUE by half and nearly doubled the number of fields classified as very efficient or as inefficient (data not shown).

Similar to NUE, a 'modest' threshold for Ns based on the median (Q2) Ns and an 'ambitious' threshold based on the Q1 Ns value were derived per crop and soil type. The EUNEP value of 80 kg N ha^{-1} for Ns aligned well with the median Ns for ware potato, starch potato, spring onion and winter wheat in clay soils (70–90 kg N ha^{-1}) and for sugar beet and winter wheat in sandy soils (80–85 kg N ha^{-1}, Table 3). However, the median Ns was considerably lower than the threshold of 80 kg N ha^{-1} for seed potato, sugar beet and spring barley on clay soils and (ware, seed and starch) potato, spring onion and spring barley in sandy soils. The Q1 Ns value was close to zero for many crops in both soil types (Table 3). These Ns targets indicate that it is possible to achieve low Ns for most crops and soil types. Yet, these targets should be further refined for multiple crops per farm to also account for risks of yield (and economic)

Table 3
Target values per soil type proposed for N use efficiency (NUE, kg N kg^{-1} N) and N surplus (Ns, kg N ha^{-1}) of arable crops in the Netherlands based on the distribution observed in the farmer field data. Q1 = first quantile, Q3 = third quantile. †The target value for negative surplus should be 0, meaning no surplus allowed.

	Ware potato	Seed potato	Starch potato	Sugar beet	Spring onion	Winter wheat	Spring barley
Clay soils							
NUE Median	0.65	0.90	0.65	1.00	0.80	0.70	0.75
NUE Q3	0.90	1.15	0.80	1.20	1.05	0.85	0.85
Ns Median	90	15	100	0	35	80	30
Ns Q1	20	−15†	40	−25†	−5	30	20
Sandy soils							
NUE Median	0.75	0.75	0.70	0.70	0.90	0.65	0.60
NUE Q3	1.05	1.10	0.90	0.80	1.40	0.80	0.75
Ns Median	60	40	65	60	20	80	50
Ns Q1	−5†	0	25	30	−25†	35	30

losses due to N limitations, and the relations between N surplus and NO_3^- leaching, NH_3 and NO_2 emissions (de Ruijter et al., 2007; de Vries and Schulte-Uebbing, 2019). As an example, an Ns of 34 kg N ha^{-1} translates into 50 mg NO_3^- L^{-1} (the nitrate limit stipulated in the Nitrates Directive) when N is diluted in a 300 mm annual precipitation surplus, so a Ns of 80 kg N ha^{-1} will result in a nitrate concentration well above 100 mg NO_3^- L^{-1} (if no major gaseous N losses occur).

4.3. 'Big data' and the EUNEP framework

The availability of comprehensive 'big data' from farmers' fields allowed to describe farmers' practices in detail (Fig. 2), to gain insights into the variability and target values for relevant indicators such as NUE and Ns (Figs. 3 and 8) and to determine NUE and Ns values prevalent across crops and soil types in the Netherlands (Fig. 4). The aforementioned features are useful to ground NUE assessments in on-farm conditions and to monitor the effectiveness of policies at local level, aspects which are entirely lacking from studies using global databases and general assumptions (Zhang et al., 2015; Lassaletta et al., 2014) or controlled N response trials. Yet, only marginal insights could be gained into the drivers of N application in farmers' fields, as reflected in the low R^2 of the fitted models (Table 2). Such low R^2 indicate that most of the variability in the response variable was not explained, which seems to be a feature of 'big data' from farmers' fields (Assefa et al., 2020; Silva et al., 2020, 2021)

The low explanatory power of statistical models in the context of farmer' field data can be attributed to different factors. Firstly, databases of farmers' field data comprise all possible sources of variation that occur in the real world, i.e., in biophysical and management factors. This contrasts with field experiments under controlled conditions or data collected in formal monitoring schemes. Field experiments aim to exclude unwanted sources of variation, which is done through replication and by ensuring uniformity in biophysical and management conditions of the treatments tested. Formal monitoring schemes, on the other hand, aim to record all key factors known or expected to affect the response variable. 'Big data' from the world of practitioners cannot ensure the features of field experiments and formal monitoring schemes, and are therefore bound to hold a large share of unexplained variance, as reported in this study (Table 2). Secondly, farmers' field data are prone to inaccuracies as they rely on farmers' ability and willingness to record management operations in detail. For instance, we note that N application methods for solid manures were misreported as it is technically not possible to inject these in the soil (Table 1), that single N application times for winter wheat are not common in the Netherlands (Fig. 6) and that nutrient contents in organic fertilisers are highly variable and uncertain (Fig. A1). It is also possible that manure applications were underestimated in some of the fields analyzed (Fig. 5). Thirdly, misspecification of statistical models as a result of poor model selection or lack of second-order terms (e.g., interactions and squared terms) can also be a cause of low explanatory power. Therefore, the analysis presented in this manuscript can be considered as a learning tool that highlights some of the limitations, and opportunities, for the use of 'big data' in agronomic research.

Using 'big data' for agronomic assessments requires assumptions on key aspects and processes that vary largely across farmers' fields. The assumption of steady state equilibrium between annual net mineralization from the soil N pool and the total annual N input into the soil N pool is essential for the EUNEP framework (Quemada et al., 2020; EUNEP, 2015). Only in steady state Ns is equal to total N loss to the environment. Soil organic matter stocks in the Netherlands have been estimated to be stable in the upper soil layer over the past decades (Janssen, 2017; Reijneveld et al., 2009), but it is unsure whether this also holds for soil N stocks. The gradual tightening of allowed manure applications (late 1980s onward), Ns (MINAS, 1998–2005) and N application standards (2006 onward) may have slightly dwindled N stocks. If this is still ongoing, it implies that our current Ns values are smaller than the equilibrium Ns (which equates to total N loss) that will ultimately result under the current input regime. The EUNEP framework as implemented here also relies on default coefficients for the N concentration in harvested products (Silva et al., 2020; de Haan and van Geel, 2013) and N replacement values of organic manures (van Dijk et al., 2004). These are the most up-to-date for arable crops in the Netherlands, but we acknowledge they hide variability between farms and years and hence, introduce uncertainties in the analysis.

5. Conclusion

This study provides an extensive example of the use of 'big data' to describe N management practices in farmers' fields and to explain variability in N indicators of crop performance, following the framework of the EU N Expert Panel (EUNEP). In conclusion, N-use efficiency in Dutch arable farming was found to be fairly high and for some crops above the EUNEP target range. Nevertheless, and as shown in this study, high NUE alone is misleading at very high N application rates as that is often associated with relatively high Ns. This set of scores is the outcome of large N inputs combined with large N outputs, causing high N-use efficiency but high N surplus at the same time. On farms where Ns is considered too high to meet environmental targets, options to reduce Ns are either to raise N offtake or to lower N input. Assessing the scope for raising N offtake by fine-tuning N management or crop breeding requires more process-oriented research. Our results suggest that such scope is limited, given already high NUE ranges and the relatively small yield gaps in the Netherlands. The practice of split N application was, unexpectedly, associated with greater total N input rather than N savings, and so did not contribute to increasing N-use efficiency. While replacement of organic fertilisers (animal manures) by mineral fertilisers would obviously reduce N surplus, complete replacement might come at the cost of soil quality and would conflict with aims of circularity. The current government policy is to replace bulk manures by processed, well-controlled products. Although costly, this might indeed allow – similar to mineral fertilizers – for more precise management based on known product properties and might contribute to better utilization of the nutrients supplied. The use of organic fertilisers is essential from a circularity and N-use efficiency point of view at regional or national levels. Future research is needed to understand how to best use organic fertilisers in the crop rotation considering phosphorus requirements and soil organic matter balance, product quality, production costs and potential risks to the environment. Finally, only 17 out of 129 farms in our sample achieved N-use efficiency above 0.75 $kg\,N\,kg^{-1}\,N$ for all crop types within a single year, which highlights the challenge of achieving consistent high N-use efficiency at farm level in the long-term.

The analysis presented in this study is crucial for monitoring N performance for different crops across different farms and over time with the purpose of motivating policies and of evaluating their effectiveness. Yet, further processed-oriented studies are needed to assess whether reducing N inputs is indeed the only remaining viable option that farmers in the Netherlands have to improve the environmental sustainability of their cropping systems.

Definitions

N input: Amount of total N applied with mineral and organic fertilisers, N in planting material and atmospheric N deposition per unit area per year.

Total N applied: Amount of mineral and organic N applied with mineral and organic fertilisers per unit area per year.

Plant available N applied: Amount of mineral N applied with mineral fertilisers and organic N applied with organic fertiliser corrected for fertilizer replacement values per unit area per year.

Authors' contribution

JVS: conceptualization, methodology, software, formal analysis, investigation, data curation, writing – original draft, visualization. MVI: methodology, validation, writing – review & editing, supervision. HFMTB: methodology, validation, writing – review & editing. LS: conceptualization, validation, resources, writing – review & editing, supervision. TRT: methodology, formal analysis, writing – review & editing. NPRA: validation, resources, writing – review & editing, supervision, project administration, funding acquisition. PR: conceptualization, methodology, validation, writing – review & editing, supervision, funding acquisition.

Conflict of interest

None declared.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2021.108176.

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