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Simplifying residual nitrogen (N_{min}) sampling strategies and crop response

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ABSTRACT

Globally, important nitrogen fertilizer decisions are often made at the early stages of plant development, when plants are not yet sufficiently indicative of their needs. Optimizing nitrogen fertilization of crops requires assessing the available soil mineral nitrogen content (N_{min}) at the beginning of the season and was assessed exemplarily for wheat and maize. Since 2020 a mandatory soil N_{min} analysis for each crop on a representative field is required in Germany in zones characterized by increased nitrate concentrations in the groundwater, encompassing approximately 28 % of the arable land. However, soil analysis is time-consuming, costly, and labor-intensive and requires further optimization beyond the current practice.

In this study, wheat fields in 2018 and 2019 and maize fields in 2018 were sampled in a grid pattern in spring, and the soil nitrate-N content was determined in 30 cm layers down to 60 cm soil depth in 11 fields and further down to 90 cm soil depth in two of the fields. For each single and the combined soil depths, all fields could be sampled with a deviation of less than 10 kg nitrate-N ha^{-1} with only two soil samples. Overall, the reduced field-specific soil sampling strategy proved advantageous compared to crop-specific, regionally representative N_{min} values offered by the official advisory authorities based on multiple averaged field investigations with an increased sampling intensity of 16 samples per field. Further, the reduced field-specific soil sampling strategy delivered more precise N_{min} values by 11.2 kg nitrate-N ha^{-1} for wheat fields and slightly less precise values by 4.8 kg nitrate-N ha^{-1} for maize fields. The reduced field-specific soil sampling has great potential to reduce analysis and soil sampling costs. Nitrogen fertilization experiments supported the usefulness of the new simplified N_{min} strategy. Multispectral in-season satellite imagery from Sentinel-2 could not adequately capture the spatial nitrate-N level differences and confirms soil samplings needs early in the season.

Because most farmers base their fertilization strategy on regionally crop-specific aggregated N_{min} values delivered by the official advisory system, we consider a simplified strategy to be more indicative of the field-specific soil N_{min} status, which is eased by a markedly reduced sampling frequency and further simplifies the analysis by aggregating the separately analyzed soil depths to only one single depth. Further, currently available simplified on-farm analyses of the soil nitrate content allow for conducting more intensive field-specific soil N_{min} analysis, thus contributing to improved nitrogen demand management and decreasing adverse environmental effects.

1. Introduction

Nitrogen is of great importance in agricultural production due to its major role in influencing the yield and quality of crops (Robertson and Vitousek, 2009; Barmeier et al., 2017; Prey et al., 2019). However, much of the nitrogen used is lost to water, air, and land, causing environmental and human health problems (Galloway et al., 2008).

To avoid environmental damages sustainable agronomic practices must be developed. A recent overview of cropping systems in Western Europe, India, and China have shown that the most important nitrogen fertilizer applications, e. g., in wheat-growing areas are made at Zadoks growth stages 23 and 31 in Europe, at planting and Zadoks growth stages 14 and 29 in India, and planting and Zadoks growth stage 23 in China (Swarbreck et al., 2019). At such early growth stages plants are not yet sufficiently indicative of their nitrogen needs and therefore visual or optical estimates of the plant nitrogen status cannot fulfill this task. This calls for the need to place more importance on the determination of mineral nitrogen at the beginning of the crop cycle. Therefore, this study aims to develop a simplified procedure to determine soil residual nitrogen before planting or in early plant growth stages and was

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exemplarily investigated for arable sites in Germany cropped with wheat and maize.

Germany`s overall nitrogen balance in 2016 showed a surplus of 98 kg ha^{-1} on agricultural land (Bundesanstalt für Landwirtschaft und Ernährung (BLE), 2018), and this value has stagnated in the last two decades. The threshold value of 50 mg/l nitrate in groundwater was exceeded by 28.2 % from 2012 to 2015 and 26.7 % from 2016 to 2018 for the examined groundwater monitoring sites in the German EU nitrate monitoring network (Bundesministerium für Umwelt et al., 2020). Areas where the abovementioned threshold for nitrate (50 mg/l) has been reached or where the nitrate concentration is 37.5 mg/l with an increasing trend are designated as "red zones" in Germany. With the German Fertilizer Ordinance (DüV) amendment in 2017, the individual federal states can tighten the regulations. As a further measure, the mandatory N_{min} soil analysis (nitrate-N + ammonium-N, "N_{min}") of fields can be prescribed before the application of significant amounts of nitrogen (BLE, 2018).

Field-related N_{min} studies evidencing challenges and possible optimizations are still relatively scarce. To further optimize nitrogen fertilization and decrease the nitrogen surplus, it is necessary to measure the residual soil mineral nitrogen more frequently (Schmidhalter, 2011). Until now, farmers in Germany could adopt the averaged regional N_{min} guideline values for individual crops. However, these values have a disadvantage in that they only represent a gross generalization and can be extrapolated to individual fields to only a limited extent. They tend to disregard the past and actual history of the individual field sites, as influenced by site-specific soil characteristics interacting with locally varying climate conditions, pre-crops and catch crops, previous organic or inorganic fertilization, and variable nitrate losses during winter-time. As a consequence, locally adopted nitrogen fertilization is far from optimal and therefore requires further improvements. Substantial investments in a higher frequency of residual nitrogen measurements need to be balanced with the additional workload and costs, not only for sampling but also for analysis. Therefore, improved strategies must be developed.

Many studies have investigated the spatial distribution of nitrate and/or ammonium in arable fields. Some authors found no spatial dependence for nitrate at soil depths down to 90 cm (Dahiya et al., 1985; Ilsemann et al., 2001). Schmidhalter et al. (1991a, 1991b) determined the spatial independence for N_{min} values of individual soil layers (0−30 cm, 30−60 cm, and 60−100 cm) to be frequent at distances greater than 10 m. Van Meirvenne and Hofman (1989) determined spatial dependences of 9.5, 23, and 34 m for nitrate-N at a soil depth of 0−100 cm in October, February, and April. The spatial dependence of N_{min} values varied considerably depending on the study. Stenger et al. (2002) reported that the geostatistical analysis of nitrate-N data provided little additional information than classical statistical methods.

To obtain representative N_{min} values for agricultural fields, it is advised to sample the entire field as long as no heterogeneity calls for a more directed site-specific assessment. However, the technical workload should be kept within limits.

Similarly, many studies addressed the appropriate field sampling schemes to obtain a representative mean value of mineral nitrogen. On a 90 × 90 m plot, Scharpf (1977) investigated the influence of increased sampling intensity. The samples were systematically collected in a square grid with a minimum distance of 30 m. From 10 soil samples onwards, no change in the mean value was observed. Those researchers recommended taking 12 samples at representative locations in a field.

Soil sampling for N_{min} in Germany often follows the official VDLUFA (Association of German Agricultural Research Institutes) guidelines. It is recommended for homogeneous soils to collect 15–16 soil samples at the nodes of a grid (30 × 30 m) evenly distributed over a field`s representative area. In principle, the composition of the sample should represent the average of the area to be examined. Depending on the homogeneity of the soil, the representative area can correspond to 1−4 ha (Hoffmann, 1997).

Many fields do not have even topography. Knittel and Fischbeck (1979) noticed higher nitrate-N contents at the foot of the slope than on the hilltop during their grid sampling of a homogeneous Cambisol with a silty loam texture and suspected that this result might be due to the thicker loess layer and the direction of water and nutrient flows. Some of the fields investigated in this study also showed significant differences in topography. Therefore, the influence of topography on soil sampling for N_{min} should be examined.

For the first top-dressing, nitrogen management decisions must be made at early development stages. Although it has been shown that differences in biomass and nitrogen status can be spectrally inferred at relatively early stages (Elsayed et al., 2018; Prey et al., 2018), it has not yet been investigated whether differences in soil N_{min} status are reflected in the biomass or nitrogen status of plants. This also raises the question of whether spectral observations of the plant status at earlier growth stages could be used as an alternative to drawing conclusions about the N_{min} value of the soil. If this possibility exists in early development stages at relevant N-fertilization dates, this could contribute to significant labor savings and cost savings. As this has not been investigated so far, this work aims to identify correlations between the soil N_{min} status and the in-season biomass development using multispectral satellite imagery.

The aims of this study were therefore to examine (i) the possible vertical distribution patterns of nitrate-N and coefficients of variation (CV) in the soil, (ii) the use of the coefficient of variation (CV) for estimating the sampling intensity of a field, (iii) the efforts required to sample wheat and maize fields for N_{min} at the beginning of the vegetation period to arrive at a meaningful representation, (iv) the influence of different distributions on the sampling intensity, (v) whether topographical differences in a field influence nitrate-N values and the sampling strategy, (vi) to compare the use of N_{min} data from the official advisory system based on aggregated region- and crop-specific N_{min} values with those obtained from a reduced field-specific sampling and analytical strategy (vii) and the possibility of using in-season multispectral satellite imagery to detect whether plants respond to nitrate-N levels within a field.

2. Material and methods

2.1. Description of the investigated sites, sampling grids, and topographical information

Sampling was performed on eleven fields in 2018 and one field in 2019, located in different typical agricultural arable farming regions in South-Germany. Soil sampling for N_{min} analysis was carried out shortly before the beginning of the vegetation for wheat in February and for maize in April at a 0−90 cm or 0−60 cm soil depth. Sampling to this depth was restricted in agreement with a recently suggested recommendation by the federal advisory institutions to reduce the workload (Bayerische Landesanstalt für Landwirtschaft (LfL), 2018a). Table 1 gives an overview of the selected fields.

In two locations, the soil sampling of the soil depth of 30−60 cm was influenced by a high stone content. Field E is located in the Munich gravel plain. Due to the high skeleton content, the soil depth of 30−60 cm could not be sampled. A visual estimate was made for field G, and the proportion of fine soil (< 2 mm) was estimated to be 85 %. Data from the German soil assessment were used to determine the soil texture and its geological formation. These data were available for each field (Bayerisches Landesamt für Umwelt (LfU), 2019).

For each field, a sampling grid was designed to consider the field size and shape using ArcGIS (ESRI, Version 10.5.0.6491). Because the literature on the spatial dependence of nitrate-N or N_{min} values is variable, a minimum distance of at least 20 m between sampling points was chosen as adequate for obtaining spatially independent nitrate-N values in accordance with previous reports (Van Meirvenne and Hofman, 1989; Schmidhalter et al., 1991a). On smaller fields, the distance of the

Table 1
Description of the sampling sites. Letters indicate locations, numbers indicate different fields at the same location, (1) sL = sandy loam, lS = loamy sand, L = loam, Mo = peat, Lö = loess, Al = alluvium, D = diluvium, (2) WRB = IUSS Working Group W.R.B. (2007).

Field	Year of sampling	Coordinates(GPS)	Sampling depth (cm)	Field size (ha)	German soil assessment data(1) and soil taxonomy according to WRB(2)	Topography	Number of sampling points	Minimal distance between sampling points (m)
A	2018	48°47′40.0″N 12°47′10.6″E	0–60	2.5	L, Lö; Cambisol, stagnic	Plane	18	20
B1	2018	48°46′24.6″N 12°41′04.8″E	0–60	12.7	L, Lö; Cambisol, stagnic	Hilly	35	50
B2	2018	48°46′22.4″N 12°40′11.9″E	0–60	4.0	L, Lö;Cambisol, stagnic	Plane	18	30
C1	2018	48°44′46.1″N 11°08′36.2″E	0–60	2.7	L, Lö; Cambisol, stagnic	Hilly	18	25
C2	2018	48°45′07.8″N 11°09′09.2″E	0–60	2.4	sL, Lö to L, Lö; Cambisol, stagnic	Hilly	18	25
D1	2018	48°11′15.8″N 10°59′35.6″E	0–60	2.8	L, Lö, D; Cambisol, stagnic	Plane	16	30
D2	2018	48°11′01.2″N 11°00′13.2″E	0–60	2.5	L, Lö, D; Cambisol, stagnic	Plane	18	25
E	2018	48°10′51.7″N 11°44′07.3″E	0–30	3.7	sL, D; Leptosol, skeletic, humic	Plane	20	30
F1	2018	48°24′11.9″N 11°42′11.7″E	0–90	12.2	L, D; Cambisol, stagnic	Hilly	21	50
F2	2018	48°24′06.9″N 11°42′26.5″E	0–90	4.7	L, D; Cambisol, stagnic	Hilly	15	30
G	2018	48°14′22.4″N 11°27′46.1″E	0–60	5.4	Mo, lS, Al; Fluvisol, gleyic, calcaric, humic	Plane	27	30
H	2019	48°10′19.8″N 10°59′25.7″E	0–60	1.0	L, D; Cambisol, stagnic	Plane	8	25

sampling points was rather reduced to reach as many measuring points as possible, on larger fields the distance was rather extended because there were enough sampling points for these fields. Peripheral areas and headlands were not sampled.

Data from the digital terrain model Bavaria were correlated with each soil layer nitrate-N values to determine the topography's influence on the investigated fields sampling strategy. Data with a grid width of 50 m were available for fields B1, C1, and C2 and 6 m for fields F1 and F2 (Landesamt für Digitalisierung and Breitband und Vermessung (LDBV), 2019).

2.2. Soil sampling and N_{min} analysis

At the sites A, B, C, D, E, G, and H, soil samples were taken with a set of two gauge augers (Pürckhauer, inner diameters of 2.5 cm for 0–30 cm and 2.0 cm for 30–60 cm depth). With the first set, the soil core from the soil depth 0–30 cm was sampled. The second set was inserted into the existing borehole, and the second soil core (30–60 cm) was sampled. Due to the smaller inner diameter scraping of the topsoil and possible contamination of the bottom soil sample could be avoided. At one site (site F), a tractor-mounted soil sampling device (inner diameter of 3.5 cm for all soil depths) was used to sample down to the 90 cm soil depth. For each sampling point, 2–5 soil samples (depending on the soil) were collected to obtain the required soil quantity. The different number of samples required was due to the cohesiveness of the soils, which in turn influenced the sample quantity in the gauge auger. Especially in the depths below 30 cm, soil sampling was sometimes not possible due to the reasons just mentioned. Since these samples were taken in a radius of about 0.75 m, it is assumed that this is the best compromise between errors due to sampling devices (Baker et al., 1989) and errors due to small-scale variability (Giebel et al., 2006). The collected soil samples were stored in ice boxes during transport to avoid unwanted mineralization, homogenized if necessary, and finally frozen for storage until analysis.

Only nitrate-N was examined in this study. This assumption is supported by several investigations showing that ammonium is only present in notably small quantities in soil (Wehrmann and Scharpf, 1979; Gutser and Teicher, 1976; Thüringer Landesanstalt für Landwirtschaft (TLL), 2010) as long as the sampling occurs before a fertilization action. From the sample of each sampling point, 80 g of soil were weighed in performed as duplicate in polyethylene bottles. The sample weight is largely following the conventional method and has proven to be useful for obtaining reproducible values due to the difficulty of homogenizing wet samples (Hoffmann, 1997). An amount of 160 mL of calcium chloride solution ($CaCl_2$; 0.01 M) was added to each soil sample and shaken overhead for one hour. The solution was filtered through a folded filter (150 mm, 80 g/m^2, AHLSTROM MUNKSJÖ, Helsinki, Finland), and the first component of the filtrate was discarded. Chemical analysis was carried out using high-performance liquid chromatography (HPLC) following Vilsmeier (1984). A dry bulk density of 1.5 g cm^3 was assumed for the calculation of the soil nitrate-N content which is frequently adopted by the official advisory institutions.

2.3. Statistics and calculations for soil sampling data and data processing and statistics for satellite imagery

Microsoft® Excel® 2019 MSO (16.0.12527.20260), IBM® SPSS® Statistics 26 software, and R software (version 3.5.2) were used in further evaluation of the data. The following statistical parameters were calculated for soil data: mean value, standard deviation, minimum and maximum value, and coefficient of variation (CV [%] = standard deviation/mean value * 100). The CV was used to compare the scatter of different samples with different mean values. Correlations according to Pearson and linear regression were also calculated. A detailed description can be found in Köhler et al. (2012). The Shapiro-Wilk test was used to test for normal distribution. The number of soil samples (n) that must be taken to be within d units of the mean value was calculated as follows:

$$n = X_{\alpha}^{2} * \sigma^{2} / d^{2} \quad (1)$$

Where X_{α} is the standard normal distribution, σ is the standard deviation, and d indicates how exactly (for example, as an absolute value in kg nitrate-N ha^{-1} of the mean value) the mean value should be estimated.

Furthermore, the regionally aggregated N_{min} values from the official advisory system ($N_{min\_official}$, Bayerische Landesanstalt für Landwirtschaft (LfL), 2018b and Bayerische Landesanstalt für Landwirtschaft

(LfL), 2019) were compared with a reduced sampling intensity (restricted to two samplings per area for a soil depth of 0−60 cm, $N_{min\_red.}$). The target value, i.e., the "true" mean value for nitrate-N, represents the mean value ($\overline{X}_{true}$) over all individual values at the sampling points (xi) on a field and is calculated according to

$$\overline{X}_{true} = \frac{1}{n}\Sigma_{i=1}^{n}Xi \quad (2)$$

The deviation from $N_{min\_red.}$ to $\overline{X}_{true}$ was calculated by adjusting Eq. 1:

$$\text{Nmin\_red.} = d = \sqrt{X_{\alpha}^{2} * \sigma^{2} / N} \quad (3)$$

Before calculating the deviation from $N_{min\_official}$ to $\overline{X}_{true}$, further assumptions were made. $N_{minofficial}$ applies to nitrate-N and ammonium-N and the total soil depth of 0−90 cm. Since in our investigation only nitrate-N values were available and mostly only a soil depth down to 0−60 cm was sampled, it was assumed that the $N_{min\_official}$ only consists of 92.5 % nitrate-N (Thüringer Landesanstalt für Landwirtschaft (TLL), 2010), and it was assumed that at a soil depth of 60−90 cm, 25 % of nitrate-N (Bayerische Landesanstalt für Landwirtschaft (LfL), 2018b) is present and deducted accordingly from the value.

The comparison of $N_{min\_red.}$ with $N_{min\_official}$ was calculated according to:

$$Comparison\ of\ methods = \left(\left|N_{min-offical} - \overline{X}_{true}\right|\right) - N_{min-red.} \quad (4)$$

The Pearson correlation coefficient was calculated between the nitrate-N values and the digital terrain model data to identify topography`s possible influence.

For satellite data, the bottom of atmosphere images from Sentinel-2 were used to determine the in-season crop response to the different nitrate-N values per field. Surface reflectance data (orthorectified and atmospherically corrected) were downloaded from Google Earth Engine. For a detailed technical description of the Sentinel-2 satellite, the reader is referred to Segarra et al. (2020). The field boundary for each field was selected as the image section. Pixels at the edge of the field that were not 100 % within the field boundaries were removed and interpolated from the nearest three neighbor pixels (equal weighting) by regression-based on k-nearest neighbors. The processed images were further visually checked for clouds, and only cloud-free images were used. The previously georeferenced nitrate-N sampling points were located within these images, and a buffer in the form of a circle with a radius of 10 m was created around each sampling point. This circle`s reflectance value for each band results from the weighted average (area fraction) of all pixels involved. Two soil sampling points on field D1 were not considered due to the proximity of a former sugar beet pile with subsequent seeding of spring wheat and the resulting differentiation in vegetation. As an observation period, April to June was chosen for wheat, and April to July for maize. These periods largely cover the developmental stages tillering to stem elongation for wheat (BBCH 20 - end of 30) and maize (BBCH 10 - end of 30). Due to the close distance of sampling points in the field, bands 1, 9, and 10 with a spatial resolution of 60 m were not used for the analysis. The following commonly used indices (Index Data Base (IDB), 2021; Prey and Schmidhalter, 2019) were calculated from the available bands:

$$REIP = 700 + 40\left(\frac{\left(\frac{4+7}{2}\right) - 5}{6-5}\right) \text{including bands 4, 5, 6 and 7} \quad (5)$$

$$NDVI = \frac{9-5}{9+5} \text{including bands 9 and 5.} \quad (6)$$

Regression between the index and the nitrate-N values (separated by soil depth) was calculated for each field and available date. The R^2 and its significance are influenced, among others, by the number of variables included in the model. In order to make the different number of soil sampling points per field (n = 8–35) comparable to each other, the adjusted R^2 was used according to:

$$\text{adjusted } R^2 = 1 - \frac{n-1}{n-k-1}(1 - R^2) \quad (7)$$

With n = number of observations and k = number of regressors (Köhler et al., 2012). The number of regressors, in this case, is always one.

2.4. Field nitrogen fertilization experiments

2.4.1. Field F1

In 2018, a nitrogen fertilization experiment was carried out in field F1. The soil of the field consisted of a mostly homogeneous Cambisol with a silty-clay loam texture. The average yearly temperature is 8.4 °C, and the average precipitation is approximately 790 mm. Winter wheat (*Triticum aestivum* L., variety Reform) was cultivated. The field was managed conventionally following local standards. Besides, the plots were fertilized using standard farming techniques (pneumatic spreader, Rauch® AERO, Germany), which resulted in relatively large plots (20m × 12m). Due to the field`s size, a completely randomized design (each N- level with four replicates) was used. Table 2 gives an overview of the N-fertilizer applications. The fertilizer form used was ammonium nitrate.

The fertilizer treatments were created in order to quantify the influence of (i) the absolute N-fertilizer quantity as well as (ii) differentiated nitrogen split applications with the same absolute amount of N (treatment 4 and 5) on agronomic and efficiency parameters. Higher N-fertilization was applied for treatment 4 at the beginning of stem elongation and treatment 5 at the beginning of vegetation. This differentiation tries to reach the N-target value of 120 kg N ha^{-1} at the beginning of vegetation (Wehrmann and Scharpf, 1979), therefore the first N-fertilization is applied based on the current N_{min} value. In this case, the low N_{min} value found in the reduced sampling led to a higher nitrogen application, and the relatively high N_{min} value adopted from the official advice led to a lower nitrogen application. Therefore, treatment 4 was chosen as the fertilization strategy following the official advice, and treatment 5 was chosen for the reduced sampling strategy. The agronomic and efficiency parameter response functions were calculated across all N- levels, including treatments 4 or 5. Consequently, the response functions differed slightly.

2.4.2. Field H

In 2019, an additional nitrogen fertilization experiment was carried out in field H. The soil of the field consisted of a colluvisol with a silty loam texture. The average yearly temperature is 8.4 °C, and the average precipitation is approximately 1000 mm. Winter wheat (*Triticum aestivum* L., variety Spontan) was cultivated. The field was managed conventionally following local standards. Table 3 gives an overview of the N-fertilizer applications. The Fertilizer treatment 3 corresponded to the farmer`s N-fertilization practice applied with standard farming

Table 2
N-fertilizer treatments at site F1 in 2018.

Fertilizer treatments	N-fertilizer application [kg ha^{-1}] in the respective growth stages			Total N-fertilization [kg ha^{-1}]
	Beginning of Vegetation	Beginning of stem elongation	Flowering	
1	0	0	0	0
2	40	60	50	150
3	60	60	60	180
4	40	90	80	210
5	90	40	80	210
6	60	90	80	230

Table 3
N-fertilizer treatments at site H in 2019.

Fertilizer treatments	N-fertilizer application [kg ha^{-1}] in the respective growth stages			Total N-fertilization [kg ha^{-1}]
	Beginning of vegetation	Stem elongation	Heading	
1	0	0	0	0
2	45	45	40	130
3	60	50	60	170
4	75	65	80	220

techniques (disc spreader). In treatment 4, the additional amount of fertilizer was manually broadcast. The treatments 1 and 2 were covered with a foil during fertilizer spreading so that no fertilizer was applied there. Subsequently, treatment 2 was also manually fertilized. A completely randomized design (each N- level with four replicates) was used with a plot size of 10 × 2 m. The fertilizer form used was ammonium nitrate.

2.4.3. *Destructive data collection and further calculations*

Plant samples were taken in each plot at BBCH (**B**iologische **B**undesanstalt für Land- und Forstwirtschaft, Bundessortenamt und **CH**emische Industrie; Meier, 2018) stages 80 and 92 for site F1 and at BBCH 77 for site H to determine the nitrogen uptake of the aboveground biomass and straw at harvest. For grain yield determination, the plot`s interior rows (2.0 m width) were threshed (Deutz-Fahr®, Germany) for site F1 and a corresponding subplot on site H to avoid effects from previous biomass samplings. For determining the dry matter content, representative subsamples were oven-dried at 60 °C until no further water loss occurred. The dried samples were milled and sieved to 0.5 mm (Brabender®, Duisburg, Germany) for subsequent analysis in the laboratory for N content by mass spectrometry using an isotope ratio mass spectrometer with an ANCA SL 20−20 preparation unit (Europe Scientific, Crewe, UK). The total aboveground plant, straw, and grain N were calculated as dry matter yield x N content. Crude protein was calculated as N content grain x 5.7 (ISO 16634-2, 2016). Straw samples were obtained only at site F1.

As for efficiency parameters, the nitrogen use efficiency, nitrogen uptake efficiency, nitrogen utilization efficiency (López-Bellido et al., 2005), nitrogen harvest index (Delogu et al., 1998), and N-balance (simplified according to OECD and EUROSTAT, 2007) were calculated. Furthermore, the N-free output (Karatay et al., 2018) was calculated with wheat prices according to Bundesministerium für Ernährung und Landwirtschaft (2019) and an assumed price for nitrogen of 1 € per kg nitrogen (exclusive application costs).

3. Results

3.1. *Nitrate-N values*

The nitrate-N contents and the coefficients of variation (CV) varied from 5.3–50.7 kg ha^{-1} and from 10 to 61 % across all soil depths, locations, and years (Table 4). Averaged over sites and crops in 2018, the soil nitrate contents amounted to 14.2, 11.1, and 5.3 kg ha^{-1} nitrate-N, and the CVs to 28, 32, and 49 % at the soil depths of 0−30, 30−60, and 60−90 cm, respectively. In general, nitrate-N values decreased, and CV

Table 4
Mean value, standard deviation (Sd), coefficient of variation (CV), minimum (Min.), and maximum (Max.) value of nitrate-N at different soil depths of the investigated sites.

Location	Sampling depth [cm]	Number of samples	Mean [kg ha^{-1}]	Sd [kg ha^{-1}]	CV [%]	Minimum [kg ha^{-1}]	Maximum [kg ha^{-1}]
A	0−30	18	18.3	4.83	26	9.1	26.1
	30−60	18	13.8	3.22	23	9.0	21.1
	0−60	18	32.1	7.39	23	19.4	45.5
B1	0−30	35	8.9	2.40	27	5.4	14.9
	30−60	33	8.4	2.44	29	5.1	14.8
	0−60	33	17.4	4.48	26	12.2	28.2
B2	0−30	18	30.0	3.01	10	26.2	35.7
	30−60	18	20.7	3.72	18	15.0	27.5
	0−60	18	50.7	4.90	10	41.9	59.4
C1	0−30	18	14.3	2.49	17	10.3	20.2
	30−60	18	8.3	3.87	47	3.4	17.7
	0−60	18	22.5	5.66	26	15.0	37.9
C2	0−30	18	12.7	5.60	44	4.8	26.4
	30−60	18	8.0	2.37	30	4.7	12.6
	0−60	18	20.6	7.17	35	10.1	34.9
D1	0−30	16	11.4	2.95	26	7.6	17.2
	30−60	16	12.7	2.95	23	7.2	18.7
	0−60	16	24.1	5.28	22	16.8	35.3
D2	0−30	18	22.7	4.19	18	18.4	32.2
	30−60	18	23.6	6.18	26	12.1	34.6
	0−60	18	46.3	9.16	20	31.0	66.8
E	0−30	20	6.8	2.48	37	3.6	14.8
F1	0−30	21	9.0	4.42	49	2.2	22.3
	30−60	21	5.3	2.91	55	0.9	11.4
	60−90	21	5.3	3.21	61	2.0	11.6
	0−60	21	14.4	6.94	48	3.1	33.4
	0−90	21	19.6	9.45	48	6.5	43.3
F2	0−30	15	5.4	1.45	27	3.7	9.5
	30−60	14	5.9	1.52	26	3.3	9.0
	60−90	13	5.3	1.97	37	2.3	9.6
	0−60	14	11.3	2.50	22	7.0	17.0
	0−90	12	17.0	3.58	21	11.3	23.5
G	0−30	27	17.2	3.83	22	11.5	25.2
	30−60	26	4.3	1.74	40	1.3	8.1
	0−60	26	21.7	4.53	21	14.1	28.4
H	0−30	8	9.3	1.76	19	7.3	11.8
	30−60	8	10.4	1.92	18	8.5	13.8
	0−60	8	19.7	2.71	14	16.2	24.6

values increased with soil depth. The CV over the total soil depth was often lower or comparable to the individual soil depths CV.

3.2. Correlation coefficients between soil-depth specific nitrate-N contents and relationships of mean nitrate-N values and correlation coefficients (CV)

The correlations of the nitrate-N contents of the upper two soil depths at different sites varied and ranged from -0.28 to 0.79 (Fig. 1).

Similar correlation coefficients could be observed at some locations and were usually positive, except for field F2. Field F2 showed notably low average contents of 5.4 kg and 5.9 kg nitrate-N ha^{-1} for the soil depths 0–30 and 30–60 cm. In contrast, other sites showing higher nitrate-N values in the topsoil were also reflected in higher values in the soil depth beneath.

Across all locations, soil depths, and years, a highly significant negative correlation between nitrate-N mean values and CVs was present in our investigation (Fig. 2). Thus, the high nitrate-N content of the soil led to lower CVs and vice versa.

3.3. Required number of soil samples

For assessing the sampling intensity of a field, the variation of the absolute deviation depending on the mean value should be used. Concerning a reasonable accuracy for the sampling error, 10 kg nitrate-N ha^{-1} is proposed in this study. The relationship between the number of soil samples and the deviation from the mean values of nitrate-N content per field for the different soil depths has been calculated based on Eq. 1 and is presented in Fig. 3.

Fig. 3a–c show that all soil depths on all fields can be sampled with two soil samples well below the specified deviation of ±10 kg ha^{-1}, regardless of size or crop.

The mean value`s maximum deviations were 5.9, 6.5, and 3.4 kg nitrate-N ha^{-1} for the soil depths 0–30, 30–60, and 60–90 cm. Since the calculated number may be lower than 1 we suggest a minimum number of 1 soil sample. The Nmin values are frequently assessed for a total soil depth of 0–90 cm or in shallower rooted crops, e.g., in 0–60 cm soil depth. For this purpose, soil samples are taken from different soil depths, and 30 cm increments are commonly used. If two or three soil layers are combined into a composite sample, this could reduce the number of samples analyzed in the laboratory to half or even only one-third, depending on the total depth examined. Fig. 3d shows that for the soil depth of 0–60 cm, deviations with a maximum 9.6 kg nitrate-N ha-1 from the mean value could be achieved for all fields with only two soil samples. Even the total soil depth of 0–90 cm could be captured with two soil samples with a maximum deviation from the mean value of 9.9 kg nitrate-N ha-1 (Fig. 3e).

3.4. Influence of the frequency distribution on the sampling intensity

To calculate the required number of samples for a given deviation from the mean value, it was assumed that the data are normally distributed. This assumption is not always correct. In most investigated soil depths, the nitrate-N contents were normally distributed (Table 5). In contrast, no normal distribution was more often observed in the topsoil than in the subsoil. In all cases, a few high nitrate-N values were responsible for right-skewed distributions. Despite deviations of individual depths from the normal distribution, the normally distributed nitrate-N values re-appear when considering the entire soil depth. The only exception to this observation is field B1, where both soil depths show log-normal values.

The assumption of an incorrect distribution has consequences on calculating the number of samples at a given error. Fig. 4 exemplifies the shift in the confidence interval due to different transformations of the data for which the required number of samples for nitrate-N of the soil depth 0–30 cm in two fields was calculated based on Eq. 1.

3.5. Influence of topography on the sampling design

Table 6 illustrates the relationship between data from the digital elevation model and the nitrate-N contents at the respective depths at different locations. Thereby, the ranges between the maximum and the minimum height above sea level on the fields B1, C1, C2, F1, and F2 were 11.7, 10.3, 9.5, 15.8, and 17.5 m. In general, the correlation was notably weak and not significant. The negative sign in about 75 % of all cases indicated slightly lower nitrate-N contents at higher positions in the fields.

3.6. Comparison of reduced sampling with values from the official advisory services

In a subsequent step, regional-based nitrate-N recommendations from the official advisory service were compared with those of a reduced sampling strategy with field-wise N_{min} analysis. For this purpose, a reduced sampling frequency of only two soil samples for the total depth of 0–60 cm for each field was chosen, except for field E with 0–30 cm. Fig. 5 shows the deviations from the "true" nitrate-N mean of the reduced sampling versus the official regionally crop-specific advisory

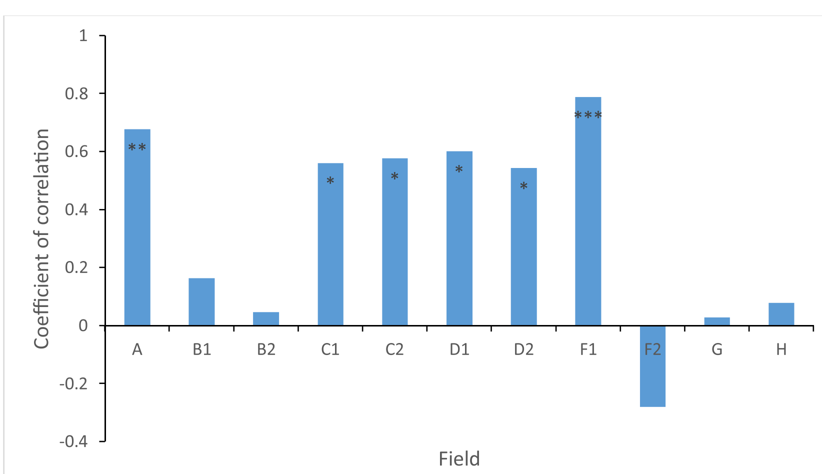

Fig. 1. Pearson correlation coefficients between nitrate-N contents of the soil depths 0-30 and 30-60 cm in different fields (indicated by letters). Asterisks indicate the significance level (* ≙ $p < 0.05$, ** ≙ $p < 0.01$ and *** ≙ $p < 0.001$).

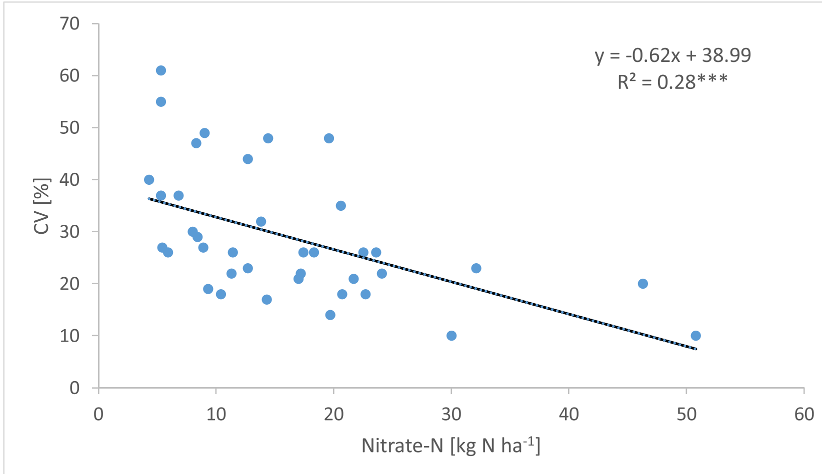

Fig. 2. Relationship between nitrate-N mean values per soil depth (0-30, 30-60, 60-90, 0-60, and 0-90 cm) and the related coefficients of variation. Data are represented across all soil depths, fields, and years. Asterisks indicate a significance level of $p < 0.001$.

recommendations in the given year.

For 75 % of the investigated fields, the deviation from the true value for reduced sampling was less than that of the official advice. This observation was particularly evident for fields cultivated with wheat, whereas this was not the case for the two investigated maize fields (fields B2 and D2).

Fig. 6 quantifies the differences between the two approaches. On average, the reduced sampling of wheat was closer to the true mean by 11.2 kg nitrate-N compared with the official recommendation based on the averaged gridded values. Reduced sampling achieved for wheat in the best case a 23.3 kg improved value (field H) and only in one case a 4.0 kg nitrate-N worse value (field A) for the estimation of the $\overline{X}_{true}$ nitrate-N value of the field in comparison with values from the official advice. However, on average, maize fields reduced sampling recorded the "true" mean value by 4.8 kg nitrate-N less than the official advisory service`s values.

3.7. Effects on N-fertilization in wheat due to the simplified strategy and the official advisory information

To investigate effects on nitrogen fertilization due to different sampling strategies data from two nitrogen increase experiments at the locations F1 and H were evaluated. In the investigated region the overall contribution of the atmospheric fallout is 10 kg N ha^{-1} year^{-1}, nitrate leaching during the main growth period of wheat from March to July varies between 5−10 kg N ha^{-1} year^{-1}, thus not contributing substantially to the nitrogen cycle in this period. Long-term results of soil mineralization during the wheat crop growth period contribute with 70 kg N ha^{-1} year^{-1} which represents the sum of residual nitrogen at early crop growth plus subsequently mineralized nitrogen from the soil pool (unpublished data). This indicates that soil mineral nitrogen at early crop growth with, e.g., 50 kg N ha^{-1} year^{-1} contributes substantially to the nitrogen requirement of a wheat crop and needs to be considered. This value is representative of the investigated year-sites. Mineral nitrogen contents can be considerably higher particularly in soils receiving frequent inputs of organic manures which was not the case in the investigated arable sites cropped with wheat.

For site F1, Table 7 shows that due to a more precise assessment of the residual soil mineral nitrogen by the reduced soil sampling strategy, on average, 30 kg N ha^{-1} is more available for N fertilization. As a result, plant N- uptake, grain yield, protein content, and grain N- uptake are increased. In contrast, the straw N- uptake is only slightly increased, and the nitrate-N content of the soil remains at the same level after harvest. In terms of efficiency parameters, the monetary income increases while the nitrogen uptake efficiency remains at the same level. All other parameters are slightly lower, with the N balance showing the most considerable difference but remaining below the required 50 kg N ha^{-1} (BLE, 2018).

For site H, Table 8 shows that reduced soil sampling increases fertilization on average by 35 kg N ha^{-1}. As a result, grain protein content, N-uptake into biomass at BBCH 77, and grain N-uptake increase. The postharvest nitrate-N content of the soil and the monetary income remains at about the same level, whereas all efficiency parameters are slightly lower except for the N-balance, which is improved.

3.8. Relationship between residual soil mineral N values and in-season multispectral satellite imagery

Relationship between spectral responses of the canopy using the indices NDVI and REIP and the field-wise N_{min} values are shown in Figs. 7 and 8. In general, only weak correlations were observed for all fields, available dates, and soil depths. Also, no significant difference was found between the tested indices.

A weak correlation between the NDVI and nitrate-N values at the soil depth 0−30 cm was observed on field D1 (Fig. 7), characterized by a relatively weak development at the beginning of the season showing minimal differences within the field. A low correlation between field emergence, soil texture, and nitrate-N values might exist. However, this was not evidenced by the index REIP, which is less suitable to detect differences in initial soil coverage (Elsayed et al., 2018).

A highly significant correlation between nitrate-N values was only observed on field C2 and the index REIP (Fig. 8). This field is characterized by a highly heterogeneous soil texture in the topsoil (sandy loam to loamy clay). The field was fertilized site-specifically at the second nitrogen application to address this spatial heterogeneity on 28 April 2018. However, only a small range of nitrate-N values was observed within the field (Table 4).

4. Discussion

4.1. Influence of vertical nitrate-N distribution and frequency distribution on field-specific N_{min} soil sampling

The correlation between the nitrate-N content of individual soil layers varied sites-specifically. Nitrate contents of lower soil depths based on the upper soil layers measured values could not consistently be estimated. In addition, it seems that a possible deep displacement of nitrate by precipitation (Venter and Gutser, 1987) of soil layers with

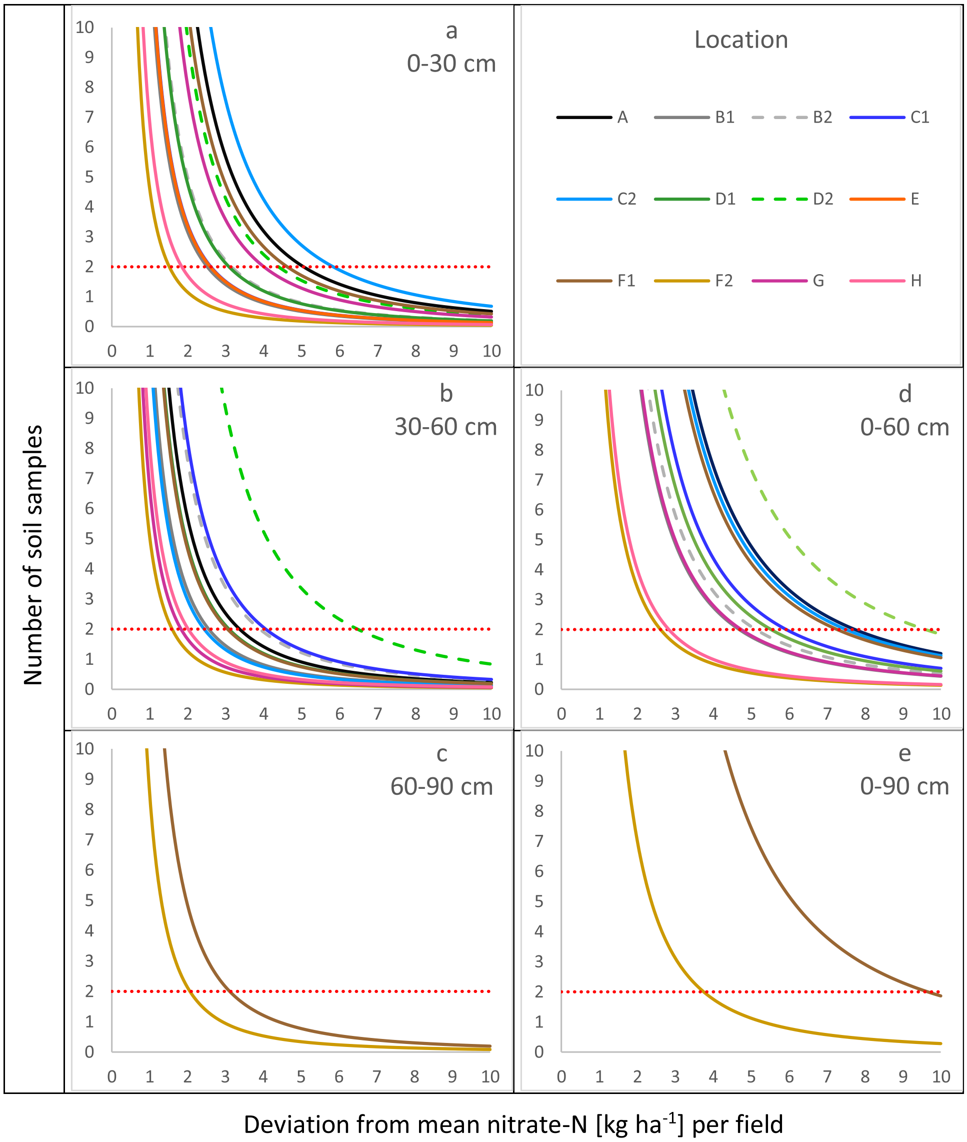

Fig. 3. Relationship between the number of soil samples and the deviation from the mean value of nitrate-N [kg ha^{-1}] content per field of each site for different soil depths (a-e). Solid lines apply to sampling in wheat at the beginning of the vegetation period, and dashed lines apply to sampling before maize sowing. A 93 % confidence interval is used. The dotted line shows the threshold for two soil samples per field.

Table 5
Distribution of nitrate-N values [kg ha^{-1}] at different locations and soil depths (N = normal distribution, Ln = log-normal distribution, Inv = inverse normal distribution," –" = no data). The p-value of the Shapiro-Wilk test for the respective distribution is shown in brackets. Using a significance threshold of 5%.

Field	Sampled soil depth (cm)				
	0–30	30–60	60–90	0–60	0–90
A	N(0.650)	N(0.622)	–	N(0.854)	–
B1	Ln(0.671)	Ln(0.515)	–	Inv(0.238)	–
B2	N(0.208)	N(0.733)	–	N(0.637)	–
C1	N(0.400)	N(0.193)	–	N(0.116)	–
C2	N(0.484)	N(0.328)	–	N(0.632)	–
D1	N(0.261)	N(0.904)	–	N(0.510)	–
D2	Inv(0.102)	N(0.968)	–	N(0.689)	–
E	Ln(0.536)	–	–	–	–
F1	N(0.065)	N(0.425)	Ln(0.157)	N(0.410)	N(0.339)
F2	Ln(0.129)	N(0.975)	N(0.821)	N(0.586)	N(0.941)
G	N(0.216)	N(0.327)	–	N(0.111)	–
H	N(0.187)	N(0.160)	–	N(0.626)	–

very low mineral N contents, as observed at field F2, to be hardly present and this also has effects on correlations between the soil layers.

Although changes in the N_{min} content concerning soil-borne-N during vegetation predominate at 0−30 cm (Peschke and Mollenhauer, 1998), Wehrmann and Scharpf (1979) observed at 20 different locations at the beginning of vegetation only small differences in the topsoil between sites but more marked differences in the N_{min} content especially of the subsoil (40−100 cm soil depth). Furthermore, Haberle et al. (2004) indicated that nitrate-N values are higher in the topsoil than in the subsoil, except for a March sampling date. Due to these different results of the vertical distribution of mineral nitrogen of the soil at the beginning of vegetation, which can spatially and temporarily markedly vary, it is recommended to sample the entire soil depth yearly.

The distribution of the data is important for the correct calculation of the number of soil samples per field. For example, the assumption of normally distributed data leads to an overestimation of the sampling intensity, as this is also described by Parkin and Robinson (1992). Frequency distributions of nitrate-N values varied from field to field as well as across soil depths. Schmidhalter et al. (1991a) observed a normal distribution for the topsoil and a log-normal distribution for the subsoil

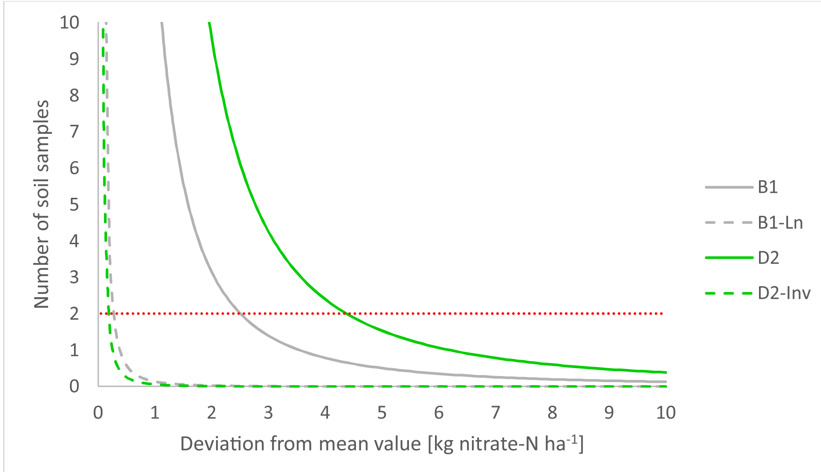

Fig. 4. Comparison of the required number of samples for nitrate-N of the soil depth 0-30 cm in two fields using different distributions. Solid line = normal distribution assumed, dashed lines = data transformed (Ln = lognormal, Inv = inverse). The dotted line shows, for example, the sampling intensity of two soil samples per field.

Table 6
Pearson correlation coefficient of nitrate-N contents and height above sea level at each site, separated by soil layer (n.s.: not significant).

Soil layer (cm)	Field				
	B1	C1	C2	F1	F2
0–30	−0.279 n.s.	0.028 n.s.	−0.206 n.s.	0.082 n.s.	−0.160 n.s.
30–60	−0.177 n.s.	−0.093 n.s.	−0.408 n.s.	−0.052 n.s.	−0.177 n.s.
60–90	——	——	——	−0.154 n.s.	0.356 n.s.
0–60	−0.245 n.s.	−0.051 n.s.	−0.293 n.s.	0.030 n.s.	−0.174 n.s.
0–90	——			−0.027 n.s.	0.065 n.s.

in their investigation of N_{min}. Van Meirvenne and Hofman (1989) observed log-normal distributions for nitrate-N values in October and February (less skewed) and normal distributions for April for the soil layer 0−100 cm. Stenger et al. (1998) observed constant as well as changing N_{min} distributions in 0−90 cm for individual fields over several years. Thus, the type of distribution can be subject to both temporal and spatial variation. In general, it is difficult to identify the distribution of the mineral nitrogen content of the soil in a field. On the one hand, non-normally distributed values might be due to large differences in soil texture, unevenly distributed fertilizers, and crop residues. On the other hand, the distribution is strongly influenced by the number of soil samples per field, which is relatively small compared with other studies and, therefore, susceptible to extreme values. This explanation is probably also the reason for the need for an inverse instead of a log-normal transformation. It can also be observed that skewed distributions tend to occur at lower mean values. However, despite the incorrect assumption of a normal distribution, each field could be reliably recorded with only two soil samples.

4.2. Relevance of the coefficient of variation, mean nitrate-N values, and topography on field-specific N_{min} soil sampling

Increasing coefficients of variation with increasing soil depth were reported by Schmidhalter et al. (1991a, 1991b) and Haberle et al. (2004), who further noted that the CV was lower across the whole soil depth than for the individual soil depths. A similar vertical distribution of N_{min} contents and CVs were observed by Schmidhalter et al. (1992). The authors noted that even small deviations at low N_{min} values resulted

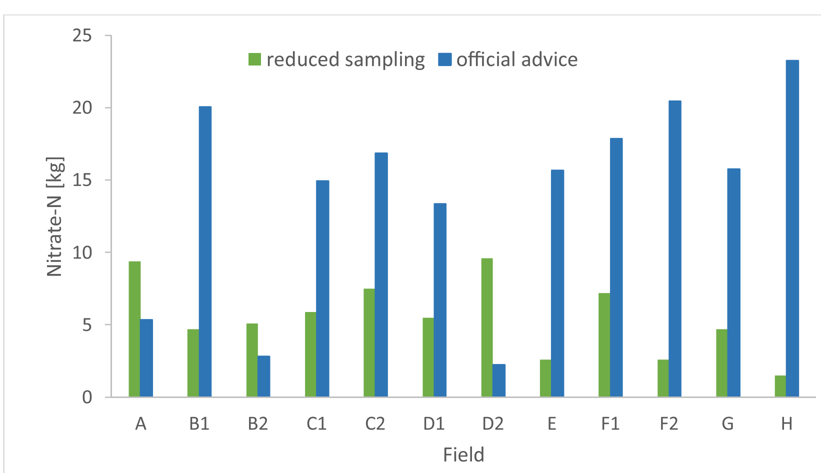

Fig. 5. Deviation of reduced soil sampling (composite sample of two samplings per field) and the regionally-based values of the official advisory information from the true nitrate-N mean of grid sampling.

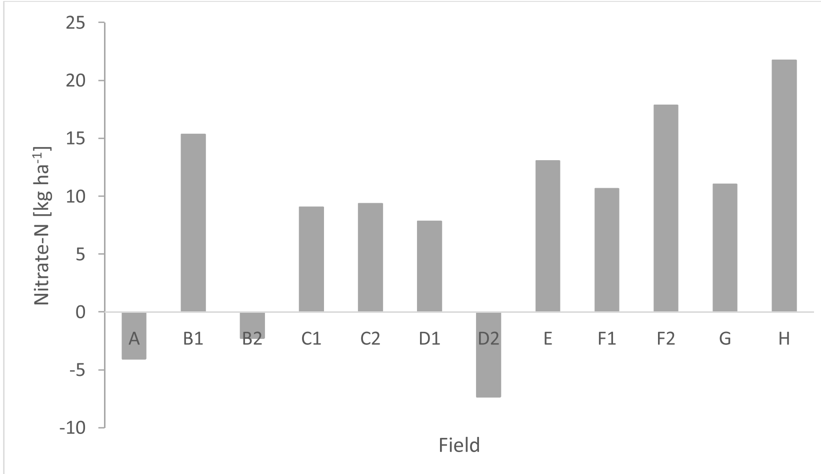

Fig. 6. Difference between nitrate-N values of the reduced sampling strategy (mixed sample of two soil samples per field of the soil depth 0-60 cm, except for field E referring to the soil depth 0-30 cm) and official advice. Positive or negative values quantify the advantages or disadvantages of reduced sampling.

Table 7
Comparison of the official advice and the reduced sampling strategy concerning N-fertilization requirement determination and agronomic and efficiency parameters of wheat for field F1. Values in brackets represent upper and lower limits of the possible sampling interval of the reduced sampling strategy.

		Official advice	Reduced sampling
Determination of fertilizer requirement	Expected yield [t ha^{-1}, 14% moisture]	8.0	
	Nitrogen demand for A/B varieties [kg N ha^{-1}]	230	
	Deduction previous crop [in this case rape, kg N ha^{-1}]	−10	
	Additional nitrogen supply from organic fertilization of the previous year [kg N ha^{-1}]	0	
	Mineral nitrogen content of the soil at the beginning of vegetation [kg nitrate-N ha^{-1}]	50	20 (10–30)
	Possible N-fertilizer application [kg N ha^{-1}]	170	200 (210 – 190)
Real agronomic parameters	Grain yield [t ha^{-1}, 14% water content]	7.73	8.11 (8.16 – 8.04)
	Protein concentration [%, related to dry weight]	12.31	12.93 (13.14 – 12.72)
	Plant N uptake, BBCH 80 [kg N ha^{-1}]	202.5	225.6 (231.3 – 219.6)
	Grain N uptake [kg N ha^{-1}]	143.6	157.5 (161.2 – 153.7)
	Straw N uptake [kg N ha^{-1}]	33.6	36.6 (38.0 – 35.3)
	Post-harvest residual soil mineral nitrogen [0−60 cm soil depth, kg ha^{-1} nitrate-N]	20.1	20.8 (20.9 – 20.6)
	N-free output [€]	1287.1	1328.7 (1328.2 – 1325.5)
Efficiency parameters	Nitrogen uptake efficiency [kg kg^{-1}]	0.84	0.84 (0.83 – 0.84)
	Nitrogen utilization efficiency [kg kg^{-1}]	38.2	35.9 (35.3–36.6)
	Nitrogen use efficiency [kg kg^{-1}]	32.2	30.0 (29.2–30.9)
	Nitrogen harvest index [%]	70.9	69.8 (69.7–70.0)
	N-balance [kg N ha^{-1}]	26.4	42.5 (48.8 – 36.3)

Table 8
Comparison of the official advice and the reduced sampling strategy concerning N-fertilization requirement determination and agronomic and efficiency parameters of wheat for field H. Values in brackets represent upper and lower limits of the possible sampling interval of the reduced sampling strategy.

		Official advice	Reduced sampling
Determination of fertilizer requirement	Expected yield [t ha^{-1}, 14% moisture]	9.5	
	Nitrogen demand for A/B varieties [kg N ha^{-1}]	245	
	Deduction previous crop [in this case maize, kg N ha^{-1}]	0	
	Additional nitrogen supply from organic fertilization of the previous year [kg N ha^{-1}]	−10	
	Mineral nitrogen content of the soil at the beginning of vegetation [kg nitrate-N ha^{-1}]	60	25 (15–35)
	Possible N-fertilizer application [kg N ha^{-1}]	175	210 (220 – 200)
Real agronomic parameters	Grain yield [t ha^{-1}, 14% water content]	12.06	11.92 (11.81–12.00)
	Protein concentration [%, related to dry weight]	12.98	13.61 (13.77 – 13.43)
	Plant N uptake, BBCH 77 [kg N ha^{-1}]	259.8	284.4 (290.9 – 277.7)
	Grain N uptake [kg N ha^{-1}]	234.9	244.4 (246.0 – 242.3)
	Straw N uptake [kg N ha^{-1}]	– –	– –
	Post-harvest residual soil mineral nitrogen [0−60 cm soil depth, kg ha^{-1} nitrate-N]	12.8	13.3 (13.3 – 13.2)
	N-free output [€]	1641.7	1586.6 (1560.4–1608.1)
Efficiency parameters	Nitrogen uptake efficiency [kg kg^{-1}]	0.96	0.93 (0.92 – 0.94)
	Nitrogen utilization efficiency [kg kg^{-1}]	46.4	41.9 (40.6–43.2)
	Nitrogen use efficiency [kg kg^{-1}]	44.7	39.3 (37.7–40.8)
	Nitrogen harvest index [%]	90.4	85.9 (84.6–87.3)
	N-balance [kg N ha^{-1}]	−59.9	−34.4 (-26.0 – -42.3)

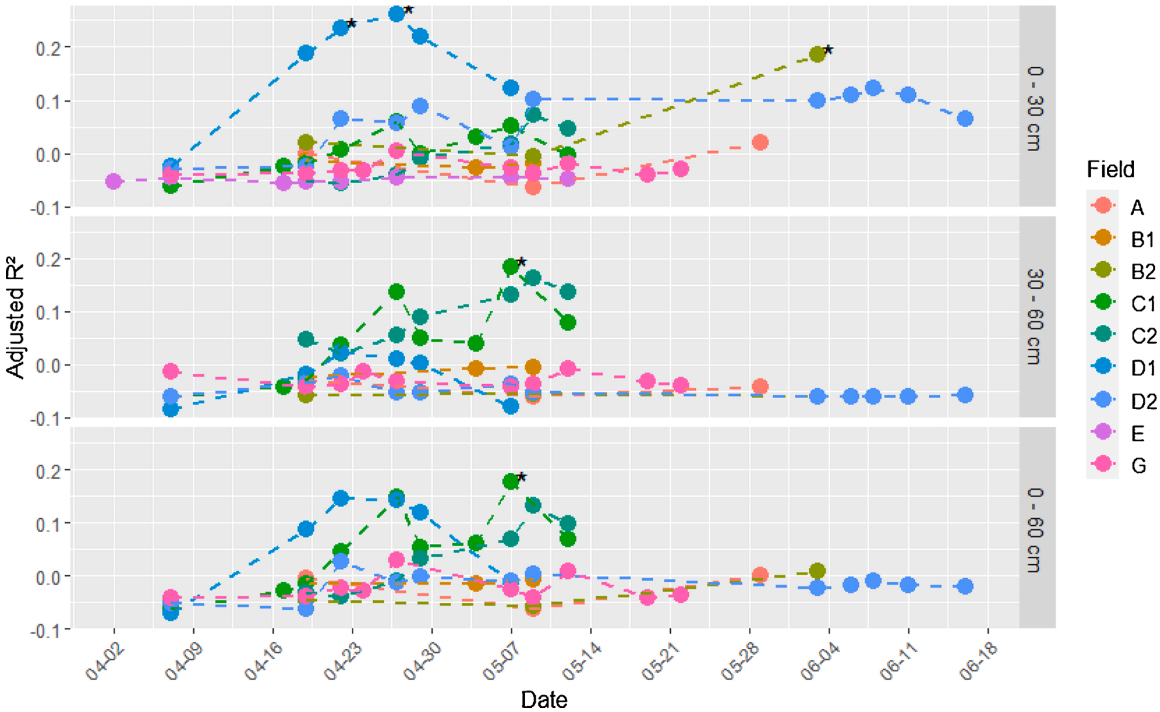

Fig. 7. Relationship (adjusted R^2) between the index NDVI (weighted mean value across all pixels within a radius of 10 m) and nitrate-N values separated by field, date, and soil depth. Asterisks indicate the significance level (* ≙ $p < 0.05$).

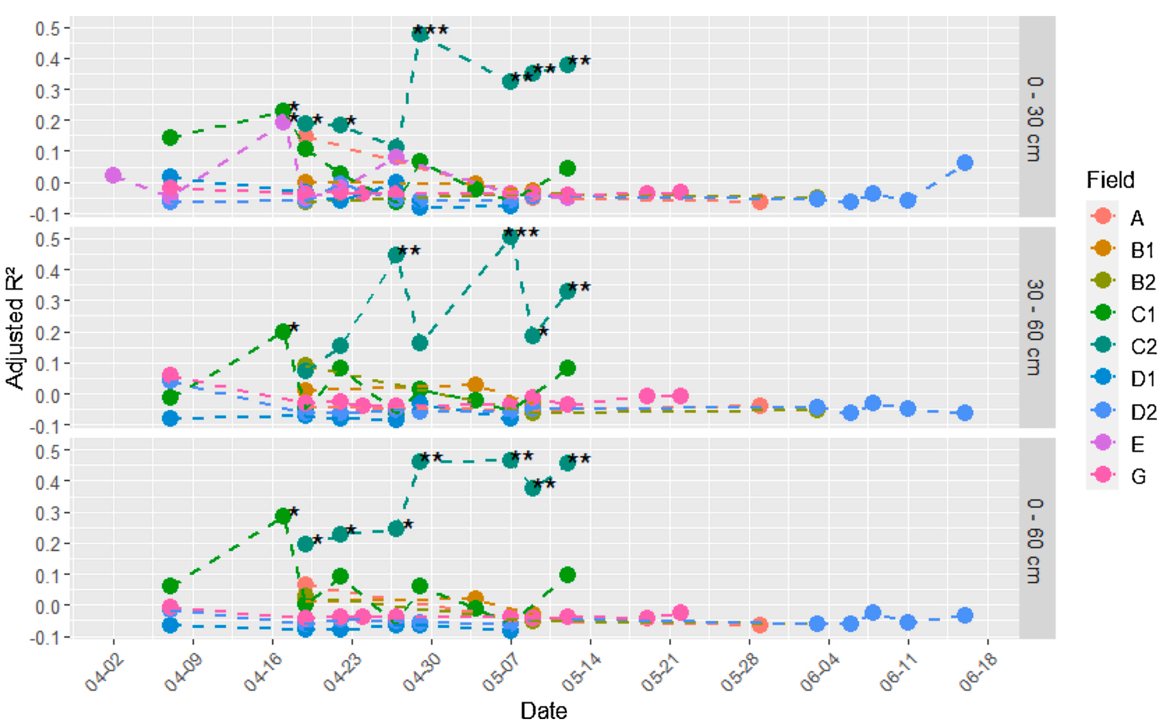

Fig. 8. Relationship (adjusted R^2) between the index REIP (weighted mean value across all pixels within a radius of 10 m) and nitrate-N values separated by field, date, and soil depth. Asterisks indicate the significance level (* ≙ $p < 0.05$, ** ≙ $p < 0.01$ and *** ≙ $p < 0.001$).

in increased CVs. This result is also viewed as a possible explanation of why CVs decrease more substantially over the entire soil depth than in individual soil depths, as the mean value of the latter is higher. The CVs are usually higher at low nitrate-N values. Although a basic requirement of regression (normally distributed data) was violated in the results presented in this paper, the regression nevertheless confirms the trend between CVs and mean nitrate-N values. In contrast, Knittel and Fischbeck (1979) found a decrease in the CV with soil depth at one site. For practical N-fertilization, the N_{min} mean level`s value is more decisive for the sampling intensity than the CV. Schmidhalter et al. (1991a, 1991b) previously reported that even increased variations at somewhat strongly increased nitrate contents, e.g., above the recommended N_{min} standard values (220 kg N/ha for maize and 120 kg N/ha for winter wheat), which occasionally can be observed in highly intensive farming systems, are of little relevance seen that at these high levels, no additional nitrogen fertilization is advised. This advice also applies and is of more practical relevance in German agriculture, depicting in general relatively moderate values to notably low N_{min} contents (≤ 20 kg N/ha). More precise recommendations are only required in the intermediate range.

Other authors have also studied the influence of topography. Franzen et al. (1998) compared different sampling strategies for nitrate-N in autumn in a 16 ha field at a soil depth of 0−60 cm over three years. The reference grid (33.5 m distance to the sampling points) was compared with grids of 67 and 100.5 m distances, a 2 ha grid, and grids that applied sampling by topography (same zones as hilltops, slopes, and low-lying landscapes). Sampling by topography was further divided into point-based (one central sampling point per zone) and area-based (mean value over all reference grid points in the respective zone) methods. The strongest and most robust correlation with the reference grid over time was found for topography area-based sampling. In contrast, other authors found no influence of topography on the spatial distribution of N_{min} values (Giebel et al., 2006). In the case of only two soil samples per field, one can be taken at lower elevations and one at higher elevations. However, in relatively small fields, as in this study, topography`s influence on nitrate-N sampling seems to be rather negligible.

4.3. Accuracy of field-specific mineral N content assessment through reduced soil sampling

The accuracy of the determination of the soil mineral N content depends on many factors. Errors related to N_{min} sampling arise, e.g., from an incorrect estimation of the stone content (Scharpf, 1977), assumption of an incorrect bulk density, insufficient representativeness of soil sampling and sample treatment (Molitor, 1982), and are also influenced by the sampling device (Baker et al., 1989). Possible errors due to incorrect estimation of the bulk density and the soil`s stone content carry greater uncertainty than the analytical error (Schmidhalter et al., 1991a, 1991b). Richter et al. (1984) quantified a total analytical error for storage, transport, and soil sample preparation in the range of 10–15 kg NO_3- N ha^{-1}. Also, they estimated an analytical error of UV spectrometry up to 5.5 kg nitrate-N ha^{-1}. Our own long-term experience in determining nitrate-N using high-performance liquid chromatography (HPLC) indicates an error of ≤ 5%. Baker et al. (1989) were able to show that, given the size of the sampling devices, smaller diameters led to lower NO_3-N kg ha^{-1} values and the earth auger with 5.1 cm was most suitable. Also, the error of small-scale variability is important for this study because several soil samples have been collected to produce the required amount of soil at one sampling point, depending on the soil. Giebel et al. (2006) determined this error to be 10.2 to 26.5 kg ha^{-1} for N_{min}-N and a soil depth of 0−60 cm at sampling distances smaller than 6 m. The cause of this error could be the inhomogeneous distribution of aboveground plant residues and straw, differing mineralization rates, and spatially differing nitrogen uptake and incorporation of plant residues. However, one of the most important error sources is non-representative field sampling, which appears with 10 kg nitrate-N ha^{-1} to be quite practical compared to the error sources just mentioned.

As shown by Kanwar et al. (1998), the number of samples per field decreases or increases depending on the confidence interval level. The confidence interval of 93 % achieved in this study is estimated to be relatively high and indicates a low risk of incorrect values. The results for obtaining a representative mean value of mineral nitrogen found in this work are largely consistent with those of other studies. Schmidhalter et al. (1991a, 1991b) investigated the spatial variability of N_{min} values for individual soil layers down to a total depth of 100 cm on a slightly undulating subfield using 100 soil samples for each of three soil layers. The N_{min} mean value for the total depth was 69.5 kg ha^{-1}. The mean value could be determined for five soil samples with an accuracy of ±23 kg ha^{-1} or ±33 %. With 15 soil samples, this accuracy could be increased by 15 %, averaging 13 kg ha^{-1}. It was also recommended that an increase in the sampling intensity at a soil depth of 0−60 cm at the expense of 60−100 cm could increase the accuracy and decrease the workload. Additionally, for the total soil depth 0−90 cm, Schmidhalter et al. (1992) evaluated a deviation of the N_{min} mean values from ±7.5−13 kg N as acceptable. These results largely agree with Schmidhalter et al. (1992), who found that at two locations, 5−13 and 2–6 soil samples were sufficient to achieve accuracy of the mean value of ±10 and ±15 kg N, respectively. For a given deviation of the mean value of less than 10 kg NO_3-N (probability level of 95 %), Ilsemann et al. (2001) found required sampling intensities of 9, 16, and 76 soil samples for three different sites. The increase in the latter value was due to an uneven distribution of liquid manure. This indicates a limitation for reduced soil sampling. Homogeneous distribution of organic fertilizers should generally be aimed at and in particular before N_{min} soil sampling.

The results apply to similarly sized fields. The inherent variability of inorganic nitrogen has been illustrated repeatedly (e.g.,Van Meirvenne et al., 1990) with results showing that nitrogen varies considerably and more or less comparably from small (1 m^2; Raun et al., 2002) to larger scales (1 ha to tens of hectares; Reuss et al., 1977; Schmidhalter et al., 1992; Giebel et al., 2006), with few differences observed irrespective of the form and availability of nitrogen. Coefficients of variation of between 30−60% have been described frequently, irrespective of the scale (Reuss et al., 1977; Schmidhalter et al., 1992). Haberle et al. (2004) recently showed that in a 19 ha experimental field the coefficient of variation of nitrate in the topsoil and subsoil (0−30 and 30−60 cm, respectively) ranged between 18–39 and 20–37 %, respectively. Therefore it seems possible to extrapolate the findings from this study also to larger sized fields. However, heterogeneous sites on markedly variable fields should be sampled separately.

The N_{min} value of the official advice is an average value based on a large sample size. Despite this large sample size, it could be clearly shown that the soil`s field-specific mineral N content could be recorded significantly better by reduced soil sampling, especially for wheat. This was because the official recommendation values for wheat were usually much higher than the measured values per field, leading to an overestimation of the nitrate-N values. In the case of maize, due to the limited data basis of the two fields, this comparison should be extended to additional cases. The reduced sampling of fields improved the estimation of a field`s residual mineral nitrogen content compared to N_{min} values offered by the official advisory system, especially wheat. This indicates that published regionalized values for many fields should be seen only as a rough guide and should not be generally applied to individual fields. Furthermore, the reduced field-specific soil sampling approach simplifies the standard N_{min} method by reducing the soil sampling by number and the analysis by combining the soil depths and therefore offers the chance to be applied on more fields. The N_{min} costs vary widely by the service provider. Presently they are about 17−20€ for laboratory analysis and 24€ for soil sampling. There is a great potential of cost reduction by reduced field-specific soil sampling.

N_{min} measurements can reliably be conducted on-site with simple quick tests. Portable devices (e.g. Schmidhalter, 2005) are practical tools and highly useful for this purpose which can be used not only by farmers but also by accredited service providers to deliver immediate on-site recommendations.

4.4. Crop response to simplified soil N_{min} sampling

For both sites, fields F1 and H, the soil nitrate-N content determined by reduced soil sampling was well below the published official advisory regional-based values (these N_{min}-values were adjusted for nitrate-N and soil depth). This resulted in a significantly higher possible N-fertilization with official advisory values at both sites according to the N-fertilizer requirement.

At site F1, the distribution of the total N-fertilizer was also varied by individual split applications. The first nitrogen application depends on plant development, weather and soil, and the N_{min} value. If, for example, a target value of 120 kg N_{min} ha^{-1} is assumed for wheat at the beginning of vegetation (Wehrmann and Scharpf, 1979) and the N_{min} content is low, the first nitrogen application should be higher. The increased and earlier applied fertilizer nitrogen was mostly absorbed, evident from the N uptake at BBCH 80. Furthermore, the N uptake efficiency was at the same level compared to the regionally crop-specific aggregated N_{min} values. Decisive parameters for the farmer (grain yield, grain protein content, grain N-uptake, and monetary income) could be increased. The important parameters from an environmental point of view (straw N uptake and postharvest nitrate-N content of the soil) remained approximately at the same level. All other efficiency parameters and the N balance were only slightly worse. This result is probably due to the weather conditions in 2018. Despite a pronounced lack of precipitation in April, the N uptake in the biomass increased at BBCH 80, however, nitrogen could not be translocated entirely into the grain due to the dryer and hotter conditions enhancing maturation.

On site H, only the absolute amount of N-fertilization at site H could be considered, not a further differentiation in the amounts of the individual nitrogen splits. Due to favorable weather conditions in 2019 at this site and long-term organic fertilization, both the grain yield and the N-mineralization determined from official advisory values were underestimated when determining the fertilizer requirement. The latter is reflected in the grain N-uptake of 90 kg N ha^{-1} of the unfertilized treatment.

The use of the N_{min} value at the beginning of vegetation in N-fertilizer requirement determination is only one component. Particularly in the early stages of cereal development, it represents a piece of important information for N-fertilizer decisions. For example, Puntel et al. (2019) pointed out that nitrate in the soil (0−60 cm) as a dynamic variable is an important factor for modeling the economic optimum N rate and the grain yield in the unfertilized plot for maize. However, if incorrect assumptions were made elsewhere in the requirement determination process, such as yield expectations or N-mineralization during vegetation, this cannot be compensated by more accurate field-specific N_{min} sampling. To estimate these parameters during vegetation, besides the current visual inspection, other methods are preferably used to estimate more precise the the N-fertilizer requirements of plants, such as, for example, the Green Window approach (Yue et al., 2015) or sensor-assisted site-specific nitrogen management (Schmidhalter et al., 2008). Also, improved soil mineral N content determination may not benefit if unfavorable and not controllable weather conditions during grain maturity reduce grain N uptake. However, it can be used to identify these sources of error and thereby avoid wrong conclusions.

4.5. Deriving crop response to simplified soil N_{min} sampling through multispectral satellite imagery

Evaluating N_{min} values by crop response using spectral information encounters many difficulties.

N uptake is relatively low in the early stages of plant development when N_{min} assessments are made. As a result, low mineral N contents already cover the N-demand, and high soil mineral N contents will not be absorbed and become manifest in the plant`s appearance. Therefore plants do not serve as a good indicator of the N_{min} status at these early growth stages. Interestingly enough, this work also shows that a moderate variation in the soil N_{min} status will not be reflected in the pursuing biomass growth as evidenced by in-season satellite imagery. To the best of our knowledge, this has not been demonstrated before. More substantial effects on biomass at this time might be due to other factors such as overlapping seeding areas or differences in field emergence caused by varying soil texture in combination also with climatic winter conditions or sowing techniques. This needs to be further investigated. Plant N uptake might reveal different N_{min} contents during vegetation but will be influenced and masked by nitrogen fertilization and is thus more likely to be detected at very low or omitted nitrogen fertilization.

5. Conclusions

Optimization of nitrogen fertilization of crops is necessary and requires a more precise knowledge of the available nitrogen in soils at the beginning of the season. This work showed that for wheat and maize, single and combined soil depths of all investigated fields could be adequately sampled using only two soil samplings per field with an error smaller than 10 kg nitrate-N ha^{-1}. This error level is considered acceptable for practical N-fertilizer applications. This study compared a reduced soil sampling strategy for a total soil depth of 0−60 cm with the mineral nitrogen values from the official advisory recommendation. On average, in all investigated fields, reduced soil sampling allowed us to detect the nitrate-N content in soils from wheat fields more precisely by 11.2 kg ha^{-1} and of maize less precisely by 4.8 kg ha^{-1} compared with the officially recommended values. These results indicate that combined with a drastically reduced sampling effort, field-specific soil sampling represents an improvement in determining the mineral nitrogen content and furthermore represents a great potential for cost reduction, both in analysis and soil sampling in the field. This improvement also makes the fertilizer requirement calculation more precise. Additional nitrogen fertilization experiments supported the usefulness of the new simplified N_{min} strategy. In-season multispectral satellite imagery did not reveal the spatial N_{min} differences and thus supports the need for soil N_{min} determination early in the season. To reduce laboratory analyses, it is further recommended to use only one composite sample of the entire soil depth instead of individual samples obtained for the individual depths that require further analysis. For further simplification, reliable rapid on-farm tests of the mineral nitrogen content could be conducted.

CRediT authorship contribution statement

Paul Heinemann: Investigation, Methodology, Data curation, Formal analysis, Writing - original draft. **Urs Schmidhalter:** Conceptualization, Supervision, Writing - review & editing, Project administration, Funding acquisition.

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.

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